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SLOPE EROSION CONTROL FOR URBAN FREEWAYS IN ARID CLIMATES

Volume I - Final Report

Prepared by:
Dennis Duffy, Ph.D., P.E.
Hilda Hatzell, Ph.D.
College of Engineering & Applied Sciences
Arizona State University
Tempe, Arizona 85287

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16. Abstract

The character and extent of slope erosion damage to urban freeways in the Metropolitan Phoenix, Arizona area was examined. The costs associated with this damage was determined and a reporting program developed to track future erosion damage. A review of existing erosion knowledge and soils within the study area was conducted. As a result of this review a comprehensive testing program was developed to predict the erosion potential of freeway slopes. This existing program incorporates both raindrop impact and overland flow induced stresses on slope surfaces. The effectiveness of vegetation in retarding erosion was also evaluated and found to be marginally effective in arid climates.

Erosion resistance of slope soils was found, in part, to be a function of maximum particle size and the amount of particle larger than 0.18 inches. Using particle size, slope, and resistance to weathering a surface protection scheme was developed that utilized rock fragments. This rock surface acts as an intensely armored surface to protect underlying soils that is effective on slopes as steep as 26 degrees. Maximum particle sizes of up to 1.5 inches with a shape factor larger than 2 were found to provide satisfactory protection.

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SI (Metric) UNIT CONVERSION FACTORS

This report uses both English and SI units with the authors selecting the unit most appropriate. The following factors may be used to convert the measures used in this report to the International System of units (SI):

1 inch = 2.52 centimeters

1 foot = 0.3048 meter

1 pound force = 453.59 grams

1 centimeter per sec = 1.9685 feet per minute

1 gallon per minute = 3.785 liters per minute

TABLE OF CONTENTS

LIST OF PLATES

LIST OF TABLES

LIST OF FIGURES

Introduction

The problems presented by erosion to society are both severe and many facetted. The loss in crop production due to erosion will severely restrict long term agricultural capability in this country. The research directed at recognizing soil erosion potential and the development of mitigation measures comes mainly from the concern over food production . The problem of erosion is not limited to agricultural concerns. Erosion along highways represents a major safety concern and produces unsightly conditions for passing motorists. These problems are heightened in urban settings because of the intensification of freeway usage.

Not to be overlooked is the cost associated with erosion along urban freeways. The expenses associated with erosion are enormous because of the diverse activities that are affected by the results. The removal of eroded material from the highway surface is only the beginning. Soil lost from slopes clogs drainage channels. In areas where protective material is used on the slopes, large costs can be associated with the maintenance and repair of that material. An example in the Phoenix Metropolitan area is the granite placed on the slopes. Granite has created excessive pump damage in some areas. Replacement of granite lost from large rills and repair of the cosmetic damage caused by small rills requires the expenditure of many man-hours.

The problem of slope protection is both a short term and a long term one. Three general conditions of the freeway slopes must be considered: 1) Protection of slopes between the completion of the grading operations and final slope protection scheme application. 2) Correction of problems with presently protected slopes that utilize either vegetation or decomposed granite. 3) Protection of all new slopes utilizing the most efficient techniques.

This research report addressed the problems associated with short and long term erosion in the study areas shown in Figure 1. The following objectives provided the initial guidelines for the research.

1. Characterization of soil resistance to erosion. Both original subgrade and plating soils needed to be examined. This characterization had to not only assess erosion potential with respect to slope but with the appropriate freeway environment as well. The latter was especially important since the freeway slopes present unique environments in terms of precipitation, wind turbulence, and solar heating.
2. Development of temporary slope protection measures which were cost effective and compatible with permanent slope protection systems. The temporary systems needed to minimize slope damage for the period of time between the completion of the grading operation and the implementation of the permanent protection systems.
3. Development of the permanent slope protection system or systems. To meet this objective proposed protective systems needed be cost efficient, compatible with freeway

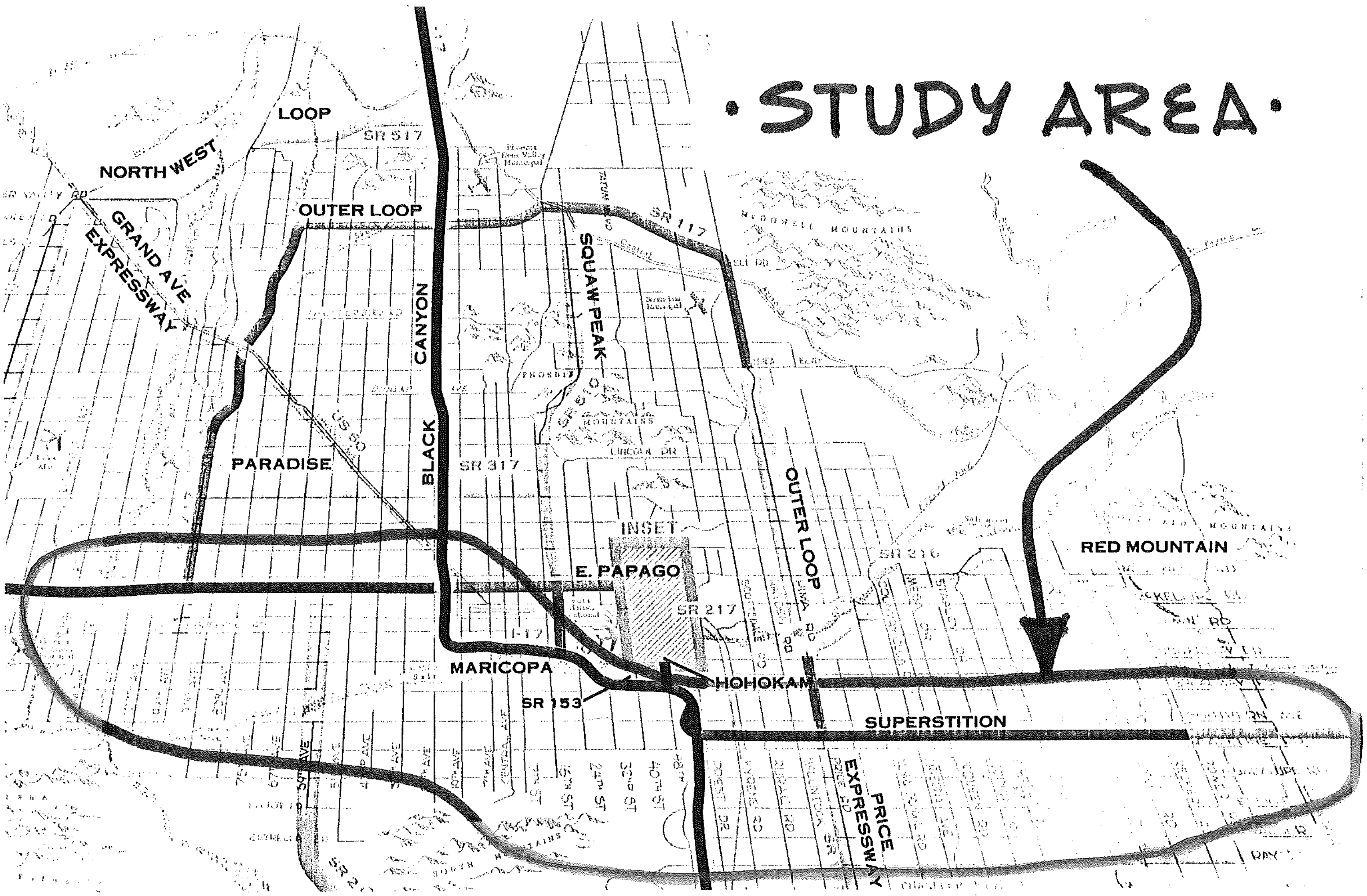

Figure 1. Study Area

ascetics, present no safety concerns to traffic, be resistive to both water and wind erosion, and relatively maintenance free.

4. Review of the existing decomposed granite slope protection material in use. Problems with this material had surfaced, and ADOT wanted to remedy these erosion related difficulties. Decisions concerning whether or not to continue with the granite, find superior alternatives, or rectify the problems by modifying the original material required additional information. Since a considerable amount of granite had already been placed, a reasonable effort needed to be directed towards finding ways to get the maximum return from the granite in place.

5. Development of slope protection systems that restrict the size of soil and granite particles transported to the pumps and drains. To minimize pump damage and reduce rates of drain sedimentation, transport particle sizes needed to be factored into the analysis. Any slope, no matter how well protected, could be expected to yield some sediment during periods of heavy precipitation. Effort needed to be directed to stopping coarse sediment particles. It was not enough to prevent the development of erosion channels on the slope, the water born sediment should also be low in coarse fractions. Proposed protective schemes should produce not only relatively small amounts of erosion, but also particles that were smaller than those brought onto the highway by traffic.

Establishment of Slope Damage

The types and locations of slope damage in the study area were determined through an extensive survey along I-10 and SR 360 during July and August of 1986, After initial assessments, the team developed an inventory for slope erosion damage (Table 1). The inventory was intended to provide information concerning the vegetation, type of slope protection, and extent of slope damage. Areas in the pre-landscaping status were divided into segments based on field observations of rill patterns and vegetation density. Each segment was sectioned by station location. A random station for each segment was evaluated using the inventory sheets.

The landscaped areas were also evaluated using a combination of the inventory sheets and an additional survey. Damage and other conditions related to the granite and plating soils were coded according to a key which had been developed from earlier field observations and is presented in Table 2. Copies of the as-built sheets were used as base maps for recording the damage keys. From these maps specific areas were targeted for inventory.

A total of 64 stations on I-10 and 57 stations on SR 360 were inventoried. Information from the inventory and the based maps containing the coded damage were combined to produce the erosion damage maps. These maps provide an overview of the erosion situation in the study area for a particular time period. Subsequent landscaping activities on I-10 have obliterated the patterns of erosion that appeared in the pre-

Table 1. Inventory Sheet for Slope Erosion Damage.

Freeway ID: I SR Team ____________________

Inspection date: __________

Vegetation: Landscaped plants Mulch ________________

Natural vegetation ___________________________

Recent Disturbance: No Yes: __________________

Slope protection: Granite No protection

Slope facing direction: N S E W

Slope angle ________ degrees Slope length __________ meters

<u>Evidence of erosion:</u>

None Rills Pedistals* Armoring _________________

*Pedistal height: ___________ *Fragment size ______________

Other ____

<u>Rill information:</u>

% of slope length containing rills ____________

# of rills = ___________ per ________ feet along detail line

Maximum rill width _______________ inches

Maximum rill depth _______________ inches

<u>Comments on erosion pattern:</u>

Table 2. Key For Damage in Landscaped Areas of SR 360.

Granite

GP - General designation for granite around plants
- GP-1 Plant brushing or sweeping - no erosion
- GP-2 Plant brushing or sweeping - erosion
- GP-3 Collapse around plant base - no erosion
- GP-4 Collapse around plant base - erosion
- GP-5 Disturbance caused by maintenance such as foot prints

GO - General designation for granite in open areas or nonplants areas
- GO-1 Collapse perpendicular to dip - no erosion
- GO-2 Collapse perpendicular to dip - erosion
- GO-3 Shrink-swell cracks - no erosion
- GO-4 Shrink-swell cracks - erosion
- GO-5 Tire tracks and skid marks
- GO-6 Gradation of size down slope

GE - Erosion around structures
- GE-1 Over curbs
- GE-2 Light posts
- GE-3 Drip emitters
- GE-4 Control valves

GC - Changes in granite characteristics
- GC-1 Color differences
- GC-2 Amount of fines

GR - Erosion rills in granite
- GR-1 Rills incised into plating material
- GR-2 Rills not incised into plating material

Soil

SP - General designation for plant areas
- SP-1 Rills between plants
- SP-2 Crusting between plants
- SP-3 Evidence of shrink-swell

SO - Open areas around plants
- SO-1 Rills
- SO-2 Crusting
- SO-3 Evidence of shrink-swell

SE - Erosion around structures
- SE-1 From emitters
- SE-2 Around control valves
- SE-3 Over concrete berms
- SE-4 Along edges of overpass apron

SA - Armoring

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landscaped surfaces. Future landscaping on SR 360 will destroy the surface recorded in these maps.

The erosion damage maps provide a valuable record that can be used for later comparison of erosional patterns that may develop. For example, differences in the erosional behavior of the granite emplaced along I-10 may be related to the interaction between the granite and the underlying soil. The maps are a historical record of the differences expressed by the soil in the pre-landscaping phase.

Of equal value to the record provided by the maps is the wealth of information that was derived from the careful observation of slope environment. These observations greatly enhanced the understanding of the researchers and influenced the later research effort; therefore, some of these observations warrant discussion.

Although the dominant form of erosion appeared to be sheet erosion from intense rainfall, other sources contributed to the damage in localized areas. The process of overland flow will be discussed in detail in the erosion index testing section. The researchers noted that the slope surfaces immediately adjacent to the concrete base of overpasses often exhibited moderate to deep rills suggesting that undirected runoff was channeling down the slopes. Observation of the rill pattern at the Dysart intersection indicated that the spacing of the rills might be related to the spacing of the bump strips along the side of the highway. Water from the road surface was channeled by the strips. Observation of the deep rills in the granite on the SR 360 overpass for the railroad track each of Country Club suggested that the highway surface on the overpass was acting as a water collection system. Runoff water was cutting a channel parallel to the direction of railroad in the freeway embankment.

Other localized sources of erosion included rills in landscaped areas caused by broken emitters in the drip irrigation lines. Soil in areas with plants but no granite often displayed a rill pattern related to irrigation sprinklers. Observation of the drainage canal along the north side of SR 360 in the vicinity of Stapely Road led to the conclusion that a major portion of the soil in the canal was contributed by the edge of the embankment adjacent to the canal and not from the slope. The upper portion of the south side of the canal embankment was not encased in concrete. Deep cuts in the soil along the unprotected embankment provided evidence of the source.

Although maintenance activities are necessary, some of these activities involve mechanical disturbance of the slopes which may have contributed to conditions conductive to erosion. Traffic on the landscaped slopes was noted as well as frequent tire impacts. Traction from tires may have helped to physically transport granite downslope. It was also noted that some rills in the granite were not filled but were cosmetically repaired by blading. The overall effect was to decrease the thickness of the granite layer for the whole area. The layer may have become too thin to provide sufficient slope protection. This observation was documented in the erosion testing.

Mechanical disturbance in the form of scraping to remove tumbleweed on I-10 may have interfered with the stabilization that was developing in the pre-landscaped areas. The scraping activity removed mulch and the upper layer of soil. Disturbance of the soil destroyed any natural armoring that had occurred and removed dormant seeds that may have provided vegetative cover. Mowing slopes on I-10 scalped existing vegetation and exposed strips of unprotected soil.

The erosion mapping process also provided an opportunity to observe the vegetation in the freeway environment. The grass in the landscaped area in the vicinity of Kyrene Rd. on SR 360 appeared to be stable. No rills were associated with it. With the exception of the bermuda grass, the landscape plants generally did not appear to influence erosion in either a positive or negative manner. Rills that began upslope were traced through plantings of Acacia redolens and appeared to be the same as rills in nearby unplanted soil. In some areas of SR 360 circular depressions in the granite were found. These patterns were always associated with an irrigated landscaped plant. The depressions were apparently related to the response of the underlying soil to wetting. In no instances were any rills in the granite associated with these depressions.

Establishment of vegetation in the pre-landscaped areas altered the erosion pattern and decreased the rill intensity. A good example of this is the grass stand on the railroad over-pass between Dysart and Litchfield Roads on I-10. The value of grass in stabilizing slopes is well established and the seeding mix used by ADOT personnel for the pre-landscaped slopes containes several grasses. Observations of the plants along the south side of SR 360 near Greenfield Road indicated that the performance of this mix may be related to the lack of available moisture during the establishment period. In the flat area, adjacent to the slope, the vegetation was growing in the rows created by the seeder. The adjacent south-facing slope contained virtually none of the same plants. Assuming that the soil was similar for each area and that both areas were seeded at the same time, the flat areas was likely to have a higher infiltration rate which would have build up the water storage in the soil. During a dry period, the plants would be able to draw from this stored water. The lower infiltration on the slope would have prevented the increase in plant available water and thus reduced the chances of establishment. The planting date should be timed to allow utilization of stored soil water during early establishment.

Slope observations made in conjunction with the erosion mapping also laid the basis sampling which occurred later in the research. It was noted that the plating soil used in the study area exhibited few differences in surface appearance. The color did not change appreciably nor did the observed texture. Later textural and phosphorus contents confirmed the observed uniformity. Three major types of granite were noted, one at Dysart Rd., one at Val Vista Dr., and one at Gilbert Rd.

Erosion Cost Program

After the extent of erosion had been established, the research team attempted to ascertain the costs associated with it. This effort proved to be time consuming and of little value. The team searched ADOT change orders associated with the study area but found little evidence of erosion related costs. Discussions with the committee overseeing this project led to the conclusion that the most likely source of erosion cost information was the maintenance records stored in the PECOS system. Natalie Rohig, Maintenance Analyst of District 1, identified four activity numbers specifically related to erosion, 169Q (cleaning of erosion material from freeway pumps and drains), 169Z (cleaning of drainage channels), 319F (granite replacement and repair), and 319H (replacement of soil lost from erosion). These descriptions are defined by the 1986-87 Performance Standards/Definitions provided by Highway Maintenance Planning Services.

The costs accumulated in these four activities for the period of March 3, 1985 through June 30, 1986 are presented in Tables 3 through 6. The laborious hand calculations required to obtain the information in these tables indicated a need for a more efficient method of data evaluation. The committee and researchers concluded that a means of accessing the PECOS records was needed. The researchers designed a cost tracking program, which is included in Appendix B. The main concept of the program was based on the realization that many of the costs related to erosion were hidden in acti-

Table 3. Erosion costs listed as dollars per mile for SR 360 Eastbound. Total erosion cost is the summation of costs associated with activities 319 F, 319 H, 169 Q and 169 Z. Slope erosion cost encompasses activities 319 F, 319 H and 169 Q.

Mile Begin	Mile End	Direc-tion	Activity 319 F	Activity 319 H	Activity 169 Q	Activity 169 Z	Total Erosion Cost	Slope Erosion Cost
0.00	1.00	East	1513.73	434.98	0.00	0.00	1948.71	1948.71
1.10	2.00	East	3490.31	436.72	0.00	0.00	3927.03	3927.03
2.10	3.00	East	682.79	223.37	0.00	0.00	906.16	906.16
3.10	4.00	East	0.00	0.00	0.00	0.00	0.00	0.00
4.10	5.00	East	0.00	0.00	0.00	0.00	0.00	0.00
5.10	6.00	East	0.00	0.00	0.00	0.00	0.00	0.00
6.10	7.00	East	0.00	74.33	0.00	0.00	74.33	74.33
7.10	8.00	East	18.29	308.24	0.00	0.00	326.53	326.53
8.10	9.00	East	30.48	501.70	0.00	0.00	532.18	532.18
9.10	10.00	East	12.19	219.51	321.53	0.00	553.23	553.23
10.10	11.00	East	0.00	0.00	562.47	0.00	562.47	562.47
11.10	12.00	East	0.00	0.00	623.39	8462.28	9085.67	623.39
12.10	13.00	East	0.00	0.00	710.75	0.00	710.75	710.75
13.10	14.00	East	0.00	0.00	147.38	0.00	147.38	147.38
14.10	15.00	East	0.00	0.00	81.97	0.00	81.97	81.97
15.10	16.00	East	0.00	0.00	38.36	0.00	38.36	38.36
16.10	17.00	East	0.00	0.00	15.34	0.00	15.34	15.34
			5747.79	2198.85	2501.19	8462.28	18910.11	10447.83

Table 4. Erosion costs listed as dollars per mile for SR 360 Westbound. Total erosion cost is the summation of costs associated with activities 319 F, 319 H, 169 Q and 169 Z. Slope erosion cost encompasses activities 319 F, 319 H, and 169 Q.

Mile Begin	Mile End	Direction	Activity 319 F	Activity 319 H	Activity 169 Q	Activity 169 Z	Total Erosion Cost	Slope Erosion Cost
0.00	1.00	West	3167.67	359.15	0.00	0.00	3526.82	3526.82
1.10	2.00	West	3262.07	365.82	0.00	0.00	3627.89	3627.89
2.10	3.00	West	622.01	150.00	0.00	0.00	772.01	772.01
3.10	4.00	West	0.00	0.00	0.00	0.00	0.00	0.00
4.10	5.00	West	0.00	0.00	0.00	0.00	0.00	0.00
5.10	6.00	West	0.00	0.00	0.00	1304.94	1304.94	0.00
6.10	7.00	West	0.00	74.33	0.00	2224.77	2299.10	74.33
7.10	8.00	West	18.29	899.09	0.00	3287.98	4205.36	917.38
8.10	9.00	West	30.48	1736.97	0.00	9694.70	11462.15	1767.45
9.10	10.00	West	12.19	613.36	321.53	9694.70	10641.78	947.08
10.10	11.00	West	0.00	0.00	562.47	1170.25	1732.72	562.47
11.10	12.00	West	0.00	0.00	623.39	4234.45	4857.84	623.39
12.10	13.00	West	0.00	0.00	710.75	18090.72	18801.47	710.75
13.10	14.00	West	0.00	0.00	147.38	2878.36	3025.74	147.38
14.10	15.00	West	0.00	0.00	81.97	0.00	81.97	81.97
15.10	16.00	West	0.00	0.00	38.36	0.00	38.36	38.36
16.10	17.00	West	0.00	0.00	15.34	0.00	15.34	15.34
			7112.71	4198.72	2501.19	52580.87	66393.49	13812.62

Table 5. Erosion costs listed as dollars per mile for I-10 Eastbound. Total erosion cost is the summation of cost associated with activities 319 F, 319 H, 169 Q and 169 Z. Slope erosion cost encompasses activities 319 F, 319 H, and 169 Q.

Mile Begin	Mile End	Direction	Activity 319 F	Activity 319 H	Activity 169 Q	Activity 169 Z	Total Erosion Cost	Slope Erosion Cost
128.00	129.00	East	0.00	3871.66	0.00	0.00	3871.66	3871.66
129.10	130.00	East	1692.36	5310.05	0.00	0.00	7002.41	7002.41
130.10	131.00	East	0.00	0.00	0.00	0.00	0.00	0.00
131.10	132.00	East	0.00	0.00	0.00	0.00	0.00	0.00
132.10	133.00	East	0.00	0.00	0.00	0.00	0.00	0.00
133.10	134.00	East	0.00	0.00	0.00	0.00	0.00	0.00
134.10	135.00	East	0.00	0.00	950.34	0.00	950.34	950.34
135.10	136.00	East	0.00	0.00	2930.12	0.00	2930.12	2930.12
136.10	137.00	East	0.00	0.00	156.28	0.00	156.28	156.28
137.10	138.00	East	0.00	0.00	1188.92	0.00	1188.92	1188.92
138.10	139.00	East	0.00	0.00	28.02	0.00	28.02	28.02
139.10	140.00	East	0.00	0.00	28.02	0.00	28.02	28.02
140.10	141.00	East	0.00	0.00	56.21	0.00	56.21	56.21
141.10	142.00	East	0.00	0.00	121.98	0.00	121.98	121.98
142.10	143.00	East	0.00	0.00	85.38	0.00	85.38	85.38
			1692.36	9181.71	5545.27	0.00	16419.34	16419.34

Table 6. Erosion costs listed as dollars per mile for I-10 Westbound. Total erosion cost is the summation of cost associated with activities 319 F, 319 H, 169 Q and 169 Z. Slope erosion cost encompasses activities 319 F, 319 H and 169 Q.

Mile Begin	Mile End	Direction	Activity 319 F	Activity 319 H	Activity 169 Q	Activity 169 Z	Total Erosion Cost	Slope Erosion Cost
128.00	129.00	West	0.00	2597.88	0.00	0.00	2597.88	2597.88
129.10	130.00	West	3368.31	2578.50	0.00	0.00	5946.81	5946.81
130.10	131.00	West	0.00	0.00	0.00	2073.93	2073.93	0.00
131.10	132.00	West	0.00	0.00	0.00	3233.65	3233.65	0.00
132.10	133.00	West	0.00	0.00	0.00	7804.20	7804.20	0.00
133.10	134.00	West	0.00	0.00	0.00	1006.71	1006.71	0.00
134.10	135.00	West	0.00	0.00	2651.89	5720.66	8372.55	2651.89
135.10	136.00	West	0.00	0.00	3487.85	1854.17	5342.02	3487.85
136.10	137.00	West	0.00	0.00	1167.98	1078.82	2246.80	1167.98
137.10	138.00	West	0.00	0.00	463.87	0.00	463.87	463.87
138.10	139.00	West	0.00	0.00	1045.00	0.00	1045.00	1045.00
139.10	140.00	West	0.00	0.00	28.02	0.00	28.02	28.02
140.10	141.00	West	0.00	0.00	56.21	0.00	56.21	56.21
141.10	142.00	West	0.00	0.00	121.98	0.00	121.98	121.98
142.10	143.00	West	0.00	0.00	85.38	0.00	85.38	85.38
			3368.31	5176.38	9108.18	22772.14	40425.01	17652.87

vities other than the four mentioned above. To account for these costs, the researchers interviewed various ADOT personnel. The activities selected for the program and the percent of erosion related cost or factor for each activity were based on the consensus of the ADOT personnel. The actual programming was completed by ADOT personnel under the supervision of Mr. John Daru.

The final version of the erosion cost tracking program should prove extremely useful to future users. The program is entitled the PECOS Roadside Activity Costing System Report/File Search Procedure. It is user interactive and utilizes the PC as the accumulator of information pertaining to the data requested. An upload-download procedure accesses the PECOS records. The time efficiency of the program has been enhanced by disk storage of records pertaining to certain activity numbers for the five years previous to the current date. Options within the program allow changes in both the activity list and factors which enable the program to be tailored to the needs of the individual users. In cooperation with the programmers, the research team wrote a User Manual for the procedure. The manual is provided in Appendix C.

Evaluation of Soils in the Study Area

Sampling and chemical analysis

The soils of the study area were examined in order to determine their variability and their limitations as plant growth media. Establishing the variability allowed the researchers to make decisions concerning other aspects of the project. Evaluating the chemical and physical properties of the soils determines what if any factors might be growth limiting to plants. Information on both variability and limiting factors will be needed in selecting test sections which are representative of the area.

Forty-two soil samples were taken in the study area. Samples of shallow depth were collected from a ten inch (25.4 cm) auger hole while deeper samples were taken with a tube sampler which was driven in by hand. The location of and general field observations for each sample are given in Appendix D.

The researchers identified three potential sources of soil variation in the study area. They were route location, soil associations present before construction, and soil environmental types after construction. The route location was selected because of potential differences in construction since the two highways that comprise the study area are not adjacent to each other.

Several soil associations exist in the area. Soil associations as defined by the USDA Soil Conservation Service represent a distinctive and proportional pattern of individual soils in a natural landscape. They are a product of the soil forming factors interacting with parent material and represent the broadest differences present in the area. Although small differences between individual soils may be obliterated by the disturbance that occurs during construction, the researchers felt that the post construction environment might still contain elements of the soil associations.

The associations present along SR 360 are described by the Soil Survey of Eastern Maricopa and Northern Pinal Counties Area, Arizona. The associations are the Laveen Association, the Mohall-Contine association, and the Gilman-Estrella-Avondale association. The associations along I-10 are described in the Soil Survey of Maricopa County, Arizona (central part) and include the Gilman-Estrella-Avondale association, the Carrizo-Brios association, and Laveen-Collidge association.

The concept of soil environment types present after construction developed from field observations and from a general understanding of the interaction of plants and soils. From a vegetation aspect, the freeway environment represents drastically disturbed land. The natural equilibrium between the plants and the soil that existed before construction has been destroyed. A new environment in a state of disequilibrium is now present. Much of what is known in traditional disciplines such as plant science and soil science does not directly apply to that new environment until the equilibrium is reestablished.

Because the drastically disturbed environment does not always conform to the expected responses of a natural landscape, new soil-plant growth units or types must be established. The freeway environment can be classified into three types of materials: plating, fill, and nonfill. Plating soil is synonymous with top soil in surface mine reclamation. It is the upper portion of the natural soil which was removed before disturbance and replaced on the surface as a plant growth medium after disturbance. This procedure recognizes the value of the natural soil and is required by law in the reclamation of lands disturbed by surface mining. The depth of this plating material in the study area is generally about two feet (0.6 meters). The source is the upper four feet (1.2 meters) of material in the excavated region of the freeway according to the as-built plans for SR 360 and I-10. For plants with fibrous root systems, the plating material may be considered the rooting zone; however, many landscape trees and shrubs have a tap root system and would be expected to extend their roots much deeper than two feet unless restricted by impenetrable layers.

The material beneath the plating soil is of two types. Fill material is placed on the existing ground surface and nonfill is the undisturbed material present beneath the ground surface. The fill material is not usually composed of natural soil since soil as a plant growth medium is described as the upper 80 inches (203 cm) of undisturbed sediment. Fill would generally be taken from the areas excavated for the highway or from an unknown source. It is subsurface material that has been mixed and compacted. If the matrix had been cemented, it was partly or completely destroyed during the emplacement process. Since the nonfill material is undisturbed subsurface material, cementation is not likely to be destroyed and may represent a serious impediment to plant roots.

Since this concept of soil environmental type has implications for the landscape design, the properties of the three types needed to be explored along with possible differences due to route location and soil associations. The sampling scheme for the soils was designed to evaluate potential differences in the plating, fill, and nonfill types.

The analysis of the 42 samples was performed on soil material which was air-dried and passed through a 2 mm sieve. The determination of the textural class of each sample was based on the percent sand, silt and clay as measured by the hydrometer method and plotted on the soil textural triangle. The pH was determined in a 1:1 ratio of soil to distilled water and measured with a pH meter. The electrical conductivity (EC) of the saturated paste extract was measured with a Beckman electrical conductivity bridge using a cell constant of 1. The available phosphorus (P) was determined by the sodium bicarbonate method which is the most common phosphorus procedure for alkaline soils in the western United States. The results from the above procedures provide information about the ability of the soils to act as a plant growth medium.

Statistical analysis

The mean value, range, standard deviation, and 95% confidence interval about the mean for the pH, percent sand, percent silt, percent clay, EC and P are provided in Table 7. Although the range for all parameters except pH appears to be wide, the small values for the standard deviation and the narrow confidence intervals indicate that the dispersion of the data about

Table 7. The mean value, range, and the 95% confidence interval for measured parameters of 42 soil samples taken from SR 360 and I-10.

PARAMETER	RANGE	MEAN	STD DEV	95% CONFIDENCE INTERVAL
Sand, %	6 - 66	40	11.97	36.3 - 43.7
Silt, %	19 - 50	32	7.70	30.1 - 34.9
Clay, %	8 - 49	28	9.43	24.6 - 30.4
pH	7.4 - 8.8	8.2	0.27	8.0 - 8.3
EC, dS/m	0.3 - 5.7	1.8	1.11	1.5 - 2.1
P, ppm	1.1 - 17.6	4.9	3.18	3.9 - 5.9

the mean is narrow. It can be deducted that the variability of these parameters in the study area is low; therefore only a few samples are needed to characterize the area.

The lack of variability also appears in the soil textural classes which are determined by the percent sand, silt and clay. The classes are listed in Table 8. along with the raw data. Thirty six percent of the samples were classified as loam, 31% were clay loam, 14% were sandy clay loam, 7% were sandy loam, 5% were clay, 5% were silty clay loam, and 2% were silty clay. The textural classes of loam and clay loam account for two thirds of the samples analyzed. The mean values for percent sand, silt and clay in Table 7 can be used to calculate an "average" soil texture for the area. A soil with 40% sand, 32% silt, and 28% clay would be classified as a clay loam bordering on a loam.

An analysis of variance (ANOVA) was used to evaluate the effect of route location, soil association, and soil environmental type. The percent sand, percent clay, pH, electrical conductivity, available phosphorus were used as dependent variables while location, association and type were independent variables. The design was a factorial but the interactions were not significant and were pooled into the error term. The results for the resulting ANOVA's are provided in Tables 9 through 13. When percent sand was used as the dependent variable, only the soil association was significant at the 0.05 alpha level (Table 9). This may be interpreted that the percent sand in the sample is related to the soil association from

Table 8. Raw data for 42 soil samples collected in study area.

(a) #	(b) Loc.	(c) Type	(d) Soil Assoc.	(e) Tex. Class	(f) % Sd	% St	% Cy	pH	(g) EC dS/m	Avail. P, ppm
1	360	F	E3	CL	31	36	33	8.4	0.3	6.4
2	360	P	E5	CL	39	31	30	8.0	2.0	6.3
3	360	F	E5	CL	39	30	31	8.2	1.2	7.0
4	360	P	E5	L	44	29	27	8.1	2.4	3.2
5	360	F	E5	L	40	36	24	8.0	2.3	5.7
6	360	P	E3	CL	25	38	37	8.3	1.5	3.1
7	360	P	E4	SCL	52	19	29	7.7	3.0	5.4
8	360	F	E4	SCL	49	20	31	7.8	2.8	5.8
9	360	P	E3	C	30	30	40	8.2	2.6	5.8
10	360	F	E3	CL	34	33	33	8.0	1.4	11.2
11	360	P	E4	CL	42	22	36	8.0	1.8	7.0
12	360	F	E4	CL	42	22	36	8.0	1.5	7.0
13	360	P	E4	SCL	42	25	33	8.2	1.4	6.3
14	360	F	E3	C	27	24	49	8.6	---	3.6
15	I10	P	C1	TC	6	50	44	7.9	4.9	7.6
16	I10	P	C3	L	45	35	20	8.5	0.5	7.2
17	I10	P	C1	TCL	19	42	39	8.0	1.6	4.3
18	I10	P	C7	L	35	39	26	8.5	0.5	4.7
19	I10	P	C7	L	33	41	26	7.8	5.7	1.7
20	I10	P	C1	TCL	14	48	38	8.4	1.0	2.7
21	I10	P	C7	L	39	36	25	8.8	0.7	2.5
22	I10	P	C1	CL	31	42	27	8.5	1.3	2.2
23	I10	N	C7	CL	31	36	33	8.1	1.9	4.2
24	I10	N	C3	CL	39	34	27	7.9	1.9	10.0
25	I10	P	C1	L	46	33	21	8.3	1.0	5.2
26	I10	P	C7	L	44	32	24	7.9	1.3	11.1
27	I10	N	C7	CL	23	38	39	8.2	0.6	2.5
28	I10	P	C1	CL	42	23	35	8.1	0.9	3.5
29	I10	P	C1	L	42	42	16	8.3	1.6	3.3
30	I10	P	C1	L	44	37	19	8.1	2.0	4.3
31	I10	N	C1	L	39	44	17	8.3	1.1	1.1
32	I10	F	C7	L	50	32	18	8.1	1.5	3.2
33	I10	P	C7	SCL	52	23	25	8.4	0.7	2.8
34	I10	F	C7	SCL	51	27	22	8.0	2.8	3.1
35	I10	N	C7	SL	66	26	8	8.2	1.6	2.0
36	360	F	E3	L	45	29	26	8.0	2.7	1.9
37	360	P	E3	SCL	50	27	23	8.2	2.9	2.0
38	360	N	E3	CL	41	22	37	8.2	2.9	4.4
39	360	N	E5	SL	62	30	8	7.9	1.3	4.6
40	360	P	E5	L	48	40	12	7.4	0.6	17.6
41	360	F	E5	L	50	34	16	8.5	1.4	2.3
42	360	F	E4	SL	57	26	17	8.4	0.8	1.9

(a) # refers to the lab number assigned for analysis.
(b) Location refers to SR 360 or I-10.
FOOTNOTES CONTINUED ON FOLLOWING PAGE

Table 8. (continued - footnotes)

(c) Type is designated as P=plating, F=fill, and N=nonfill.
(d) Soil associations are described by the name and survey:
- E3 = Laveen association, Eastern Maricopa
- E4 = Mohall-Contine association, Eastern Maricopa
- E5 = Gilman-Estrella-Avondale association, Eastern Maricopa
- C1 = Gilman-Estrella-Avondale association, Central Maricopa
- C3 = Carrizo-Brios association, Central Maricopa
- C7 = Laveen-Collidge association, Central Maricopa

(e) Textural classes are abbreviated as:
- CL = clay loam
- L = loam
- SCL = sandy clay loam
- TC = silty clay
- TCL = silty clay loam
- SL = sandy loam

(f) %Sd = % sand; %St = % silt; %Cy = % clay.
(g) dS/m is deciseimens per meter and is equivalent mMho/cm.

Table 9. Analysis of variance table for percent sand.

DEPENDENT VARIABLE: SAND   R-SQUARE = 0.303423

SOURCE	DF	SUM OF SQUARES	F VALUE	PR > F
MODEL	7	1781.70104746	2.12	0.0685
LOC	1	228.66666667	1.90	0.1770
TYPE	2	221.80556226	0.92	0.4075
ASSOC	4	1331.22881853	2.77	0.0430
ERROR	34	4090.29895254		
CORRECTED TOTAL	41	5872.00000000		

Table 10. Analysis of variance table for percent clay.

DEPENDENT VARIABLE: CLAY R-SQUARE = 0.272320

SOURCE	DF	SUM OF SQUARES	F VALUE	PR > F
MODEL	7	991.89784674	1.82	0.1158
LOC	1	82.88095238	1.06	0.3098
TYPE	2	85.94158301	0.55	0.5813
ASSOC	4	823.07531135	2.64	0.0507
ERROR	34	2650.50691517		
CORRECTED TOTAL	41	3642.40476190		

Table 11. Analysis of variance table for pH.

DEPENDENT VARIABLE: PH R-SQUARE = 0.146554

SOURCE	DF	SUM OF SQUARES	F VALUE	PR > F
MODEL	7	0.42863466	0.83	0.5667
LOC	1	0.11523810	1.57	0.2188
TYPE	2	0.06682639	0.46	0.6382
ASSOC	4	0.24657017	0.84	0.5097
ERROR	34	2.49612725		
CORRECTED TOTAL	41	2.92476190		

Table 12. Analysis of variance table for electrical conductivity (EC).

DEPENDENT VARIABLE: EC R-SQUARE = 0.037361

SOURCE	DF	SUM OF SQUARES	F VALUE	PR > F
MODEL	7	1.83971186	0.18	0.9871
LOC	1	0.29109408	0.20	0.6555
TYPE	2	0.39500784	0.14	0.8720
ASSOC	4	1.15360995	0.20	0.9361
ERROR	33	47.40223936		
CORRECTED TOTAL	40	49.24195122		

Table 13. Analysis of variance table for available phosphorus (P).

DEPENDENT VARIABLE: P R-SQUARE = 0.213830

SOURCE	DF	SUM OF SQUARES	F VALUE	PR > F
MODEL	7	88.59063019	1.32	0.2706
LOC	1	20.44023810	2.13	0.1533
TYPE	2	9.32558084	0.49	0.6188
ASSOC	4	58.82481126	1.54	0.2141
ERROR	34	325.71341743		
CORRECTED TOTAL	41	414.30404762		

which it was derived but not to the route location or the soil environmental type. When percent clay was used as the dependent variable in the ANOVA, the soil association was very close to being significant at the alpha level of 0.05 (Table 10). The relationship between soil association and soil physical properties such as particle sizes is to be expected. As mentioned earlier the soil associations represent broad differences across landforms. Some of these differences are due to type of parent material which in turn is related to soil texture.

The results are different when soil chemical properties are considered. None of the main effects of location, type, or association were significant when the dependent variable was pH (Table 11). Only 3% of the variability of the electrical conductivity can be explained by location, type, and association (Table 12). The same factors were also not significant when available phosphorus was the dependent variable (Table 13). Differences in soil chemical properties in the study area are not directly related to the route location, the soil association, or the environmental type.

Several conclusions can be drawn from the statistical analysis described above. If soil associations have been established by a soil survey completed by the Soil Conservation Service, the associations may become a useful planning tool in identifying areas that would be expected to show differences in soil physical properties. The amount of sand and clay greatly influences the infiltration and water holding capacity of the soil as well as its susceptibility to compaction. These properties are important to plant establishment and survival. The information from the soil associations could be supplemented with bore holes logs to provide a better evaluation of the expected properties of the plating soil and fill material.

Another conclusion that may be drawn is that plating soil may not have been necessary in this area since the soil environmental type did not relate to any of the properties measured. The researchers would caution against using this information to discontinue the use of plating soil. It would appear that the plating soil of the study area is similar to the sampled fill and nonfill. The results may not be applicable to other areas. For instance, observation of the construction area for the pump house at I-10 and 7th Street in May, 1987 indicated that plating soil would be absolutely necessary. The upper 10 feet (3.0 meters) of the cut consisted of light brown, fine grained, soil-like material. Beneath the upper layer was river gravel characterized by smooth stones whose longest dimension was roughly 10 inches (25.4 cm). The upper portion of the granite did not appear to be cemented but with depth the matrix appeared almost rocklike. In this section of the freeway, a finished slope face would extend into the gravel and possibly into the cemented zone. Plants placed directly in the gravel would experience water problems since not enough fines were present to insure good water supply to the plants. The cemented zone would not support plant life.

Suggested criteria for plating soil

Perhaps what is needed are criteria as to when a plating soil is required. These criteria should be based on the physical and chemical properties of the material that is expected to act as the root zone. Without plating soil, the growth medium becomes the fill material placed above the ground surface and the undisturbed material present along the cut faces of the slopes. For any location if either or both of these materials can be judged suitable as a plant growth medium, then they could be used in place of the plating soil.

Suggested criteria for suitability are based on texture, density, and chemical parameters. The texture of the material that is less than 2 mm (#10 screen) should be loam or an associated loamy texture such as clay loam, silt loam, silty clay loam, sandy loam or sandy clay loam. Less acceptable textures would be clay, sandy clay, silty clay, silt, loamy sand, or sand. The amount of coarse fragments (greater than 2 mm) should probably not exceed 35% by volume. These textural criteria insure good water holding capacity and provide a potentially high cation exchange capacity which is needed for plant nutrient supply. Only three samples in Table 8 have one of the less desirable textures; two are plating soils, and one is fill material.

In all situations, the plants should still be planted in a pit excavated in the surface material. If the rooting zone is comprised of fill or nonfill, then a larger pit might provide a better opportunity for the plant to become established. The pit should contain good quality topsoil amended with fertilizer and/or organic material. Analysis of the available phosphorus in the study area indicates that the levels are generally low. A rule of thumb used in for agronomic plants is that the sodium bicarbonate extractable phosphorus should be above 5 ppm. Levels between 5 and 10 ppm indicate sufficient phosphorus for moderate growth. Plants growing in soils with greater than 10 ppm P generally do not show a response to additions of phosphorus fertilizer. Twenty three soil samples in the study area had values less than 5 ppm while only four had more than 10 ppm (Table 8).

It should be noted that problems might arise if the texture of the material used in the plant pit differs strongly from the surrounding surface material. If the texture of the surface material is much coarser than the material in the pit, irrigation water will not move readily across the contact between the two materials. This will result in restriction of the roots to the pit which increases the chances of wind throw and reduced survival under stress. On the other hand, if the texture of the surface material is much finer than the pit material, then the water will be drawn away from the pit material. In the early stages of growth, the plants could be damaged by a lack of available water. The amount of irrigation water applied must be adjusted to compensate for the loss of water from the root growth area when the plants are first established. After establishment, water application should be readjusted to encourage the plants to explore the material outside the pit. High water rates will retard root exploration since sufficient water will be available.

The density of the root zone materials should be in the same range as the surface soils of the area. Many of the landscape plants currently in use are natives to arid areas and are generally adapted to the soil conditions of the region including the soil density. Examination of some of the borings made on SR 360 and I-10 indicates that the blows per foot with a 1.4" I.D. standard penetration spoon sampler might be used as the density criteria. In general non-cemented materials with suitable textures appeared to have SPT values from 10 to 75 blows/ft. This range included dry and moist samples. Most of the material in the portion of the core that would be exposed as the slope face or used for fill should show a density that requires less than 75 blows/ft.

Two important chemical parameters are pH and EC (electrical conductivity). The pH will provide an indication of the exchangeable bases (Ca, Mg, Na, and K) present on the soil cation exchange sites. These bases are essential for plant growth. It also provides information on nutrients that might be insoluble. For instance, at pH values greater than about 6.5, micronutrients such as Fe, Zn, Cu and Mn are very insoluble in solution. Plants that have evolved in areas where the soil pH is greater than 7 may have difficulty obtaining these micronutrients from the soils of the study area.

The pH can also indicate sodium problems in normal surface soils. A soil with a pH greater than 8.5 has a potential for moderate to high levels of sodium. The acceptable pH range is between 6 and 8.5. If the pH is greater than 8.5 then the sodium adsorption ration (SAR) should be evaluated. The SAR is a good indicator of sodium since it accounts for the mitigating effect of Ca and Mg. Only one sample in Table 8 had a pH value greater than 8.5. The lack of high pH values and the calcareous particles observed in the soils suggest that sodium is not a problem in the study area.

The EC provides an indication of the salt content of the soil. For most agronomic plants EC values greater than 4 dS/m (equivalent to 4 mMho/cm) will strongly affect plant growth and survivability. Since the salt tolerance of native landscape plants is not actually known, the 4 dS/m should be used as a conservative guideline.

The number of samples needed to establish whether the material on the cut face or the fill material is acceptable plant growth medium must be established. As expected, the more variable the material is, the more samples are needed to characterize it. Perhaps one or more samples within each half mile interval may be sufficient. If 90% of these samples meet the plant growth medium criteria, then the material could be deemed suitable for plant growth.

Separation of environments

A second issue in the use of plating soil should be addressed. This concerns changing the design concepts of the freeway in order to segregate the engineering environment from the plant growth environment. In this situation the environment refers to the parameters that must be present to fulfill the design standards. The two environments are usually inversely related. What is a good environment by engineering standards generally is a poor environment for plant growth. For instance, the slope materials must be compacted to insure the stability of the slope (engineering environment); however, compaction of plant growth medium (plant environment) increases resistance to root penetration and water infiltration at the surface resulting in poor plant growth and survivability.

An example of the segregation of two environments would be the restriction of deep-rooted shrubs and trees to the areas at or above the existing ground surface. The region above the existing ground level is composed of fill material and is dominated by the plant environment. The emplacement of the fill disrupts cemented zones in the original material which may allow better water infiltration and percolation.

In the above example, the undisturbed area below the existing ground level on the slope face is dominated by the engineering environment. If plants are not located on this portion of the slope, then plating this area may not be needed. Properties of the undisturbed material such as its density and its ability to armor could be utilized in the slope stabilization.

Erosion Index Testing of Slope Materials

The study team began the program of assessing slope erosion by reviewing available literature. In Appendix A summary of the literature reviewed and major topic grouping of each source is provided. A great deal of information on the Universal Soil Loss Equation and modifications to this predictive equation were found. There are two basic problems with using predictive techniques such as the Universal Soil Loss Equation and those of a similar genre to predict slope erosion. These are:

1. These predictors of erosion require parameters for soil and events that are difficult to predict or quantify. For example soil erodibility is a key parameter and extremely difficult to predict especially for highway slopes which experience both construction and maintenance activities. Unfortunately, the more parameters that must be input into the predictive equation, the greater the potential to err in determining a parameter. This potential is coupled with the fact that most applications in which the result is checked against the predicted erosion are in rather flat laying sites.
2. The effects of changing slope erosion resistance with time are also not considered in the predictive techniques reviewed. The research team has observed that most soils and rock masses develop increasing resistance to erosion with time. The predominant reason in soils for this increasing resistance is due to the armoring of the surface by the larger particles present in the soil. This protection tends to become more effective with time as the surface concentration of the larger particles increases. The reason for the increasing concentrations of larger particles is the removal of sand size and finer soil

particles. The larger particles are in effect left behind. As the coarse particle concentrations grow at the surface, the underlying soil becomes ever more protected. The underlying soil is protected until an erosion event severe enough to remove the coarse accumulations occurs. The research team concluded that any attempt to predict erosion must incorporate a simplified assessment of slope erosion resistance and must consider the change in erosion resistance with time.

In the previous discussion, the importance of the coarse size fraction in changing resistance with time was mentioned. However, the review of the literature failed to provide real guidance on how erosion resistance was related to size distribution and surface protection. The literature that was discovered applied to cultivated fields. Though numerous examples of slope armoring can be found, the authors were unable to find any quantification of the experience of others concerning armoring of slopes.

Development of the Research Program

The study team initially proposed to develop an index to erosion testing program which would reference slope material erosion to actual slope materials where a history of erosion was available. To accomplish this objective, it was decided to select several sites along SR 360 and I-10 in the greater Phoenix Metropolitan area as index sites. Samples of those site surface materials would be tested under a simulated rainfall that was the same as the predicted 50 year 30 minute event. The test duration, at this event's fall rate, would be determined as the testing began. The samples to be tested were to be placed into 2.0 by 2.0 ft panels. The testing would then proceed by placing the panels at predetermined slopes and then use spray heads to apply the precipitation.

Once the erosion performance of the materials was determined, that performance would be compared to observed slope erosion behavior. Additional materials not taken from existing slopes would also be tested and their performance indexed to the known slope performance.

Observations of Slope Damage

The planned program was modified, however, as a result of a storm that occurred during October 1986. This storm produced significant erosion damage on several sections of SR 360. The freeway was closed due to slope material that had been washed from the slopes. Slope damage west of Gilbert Road, can be seen on Plate 1.

The study team took the opportunity to examine the slope damage and noticed several phenomena that provided insight into the slope erosion processes. When Plate 1 is examined, the visible erosion pattern is striking. Not only is the density of the rills high but their spacing is remarkably uniform. The rills also start at the same location on the slope. Plate 2 presents a side view showing the rill start point relative to slope curvature.

Plate 1. Slope Damage SR 360 West of Gilbert Road.

Plate 2. Profile of Slope Erosion Damage, West of Gilbert

The slopes in this section were protected with approximately 0.5 to 1.0 inches of granite slope protection, which when sampled was designated as SRG8 for later reference. The profile of the slope shown in Plate 2 is provided on Figure 2.

The authors concluded from these observations, and others along the alignment that in terms of erosion what stressed the slopes the most was the overland flow contributed from the upper slope segments. When Plate 1 is reviewed, the relationship between the upper slope reach that contributes water to the steeper lower segment is apparent. It was the water delivered to the break in slope shown on Plate 2 that created the slope damage. It is the overland flow, which when combined with the precipitation falling on the lower slope segment, that cuts the rills. Though raindrop impact and lower slope precipitation contribute to slope destabilization and transport of particles, it is the overland flow that arrives in microdrainages that controls the slope erosion forces. The mean spacing of the rills on Plate 1 varies but is approximately 3 feet. The upper slope microdrainages which were observed to range from approximately 3 to 8 feet are suspected to be a function of upper slope segment slope, upper segment length, and quality of grading.

The implications of the upper slope overland flow observations are numerous. The first one that the research team addressed was the erosion index testing program. It was clear that any erosion testing program that was expected to predict slope material resistance to erosion must consider overland flow. Overland flow is hereafter defined as water delivered to a slope surface via a microdrainage system.

It was recognized that any slope protection scheme that was under consideration must also resist an overland flow contribution to erosion if it were to survive on the slope. The observation of slope damage also made it clear that slope design and maintenance procedures should minimize the amount of slope surfaces that received flow via these channels.

The granite thickness west of Gilbert Rd. was less then the original thickness which was supposed to be placed at a thickness of 2.0 inches. During the preparation of the research proposal the study team had noticed that the granite surface protection on most slopes was much thinner than expected. When the eroded slopes were examined, it was discovered that previous rills had been filled by blading the slope granite into them. Earlier storms had cut rills through the original two inch thick protection. These early rills when filled, contributed to the decreasing thickness of the surface protection.

West of Val Vista Rd. on SR 360 is another example of slope damage as shown in Plate 3. When the plate is examined, it is apparent that the rills exist essentially only in the planted areas. Rills were not found on sections of the slopes where plants had not been placed. The surface protection on these sections as well as where Plate 3 was taken is a granite designated SRG1. This granite was placed in the spring and summer of 1986 and was not only approximately 2 inches thick but also contained larger particle sizes than did the SRG8 mate-

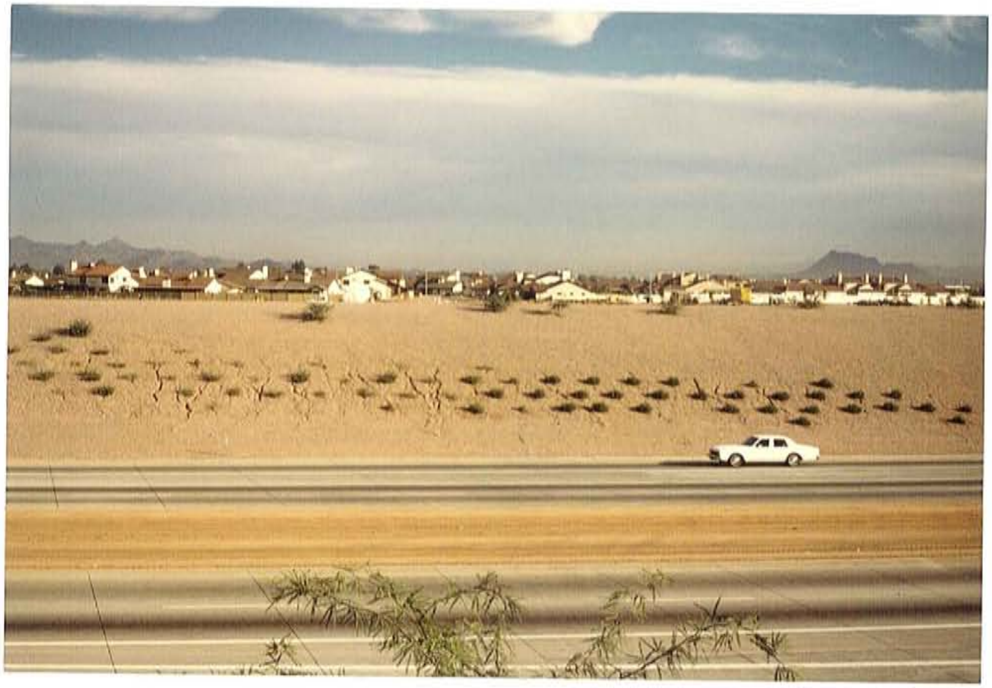

Plate 3. Dlope Damage SR 360 West of Val Vista Road.

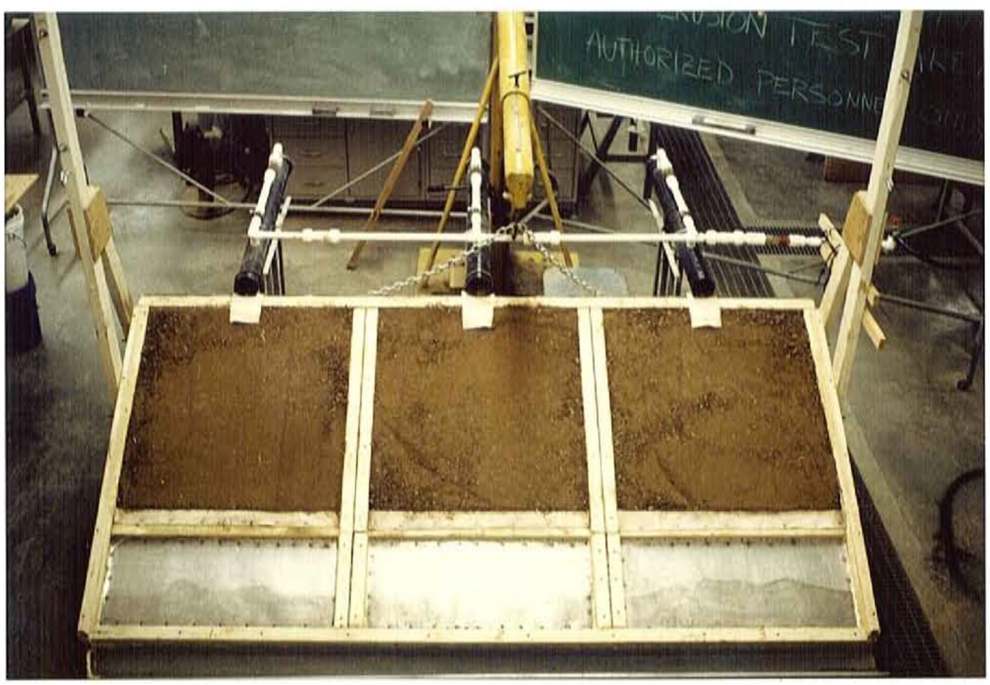

Plate 4. Front View of Erosion Test Cell

rial. The observations at this location led the study team to suspect that the low density soil beneath the SRG1 material had allowed undermining of that material to occur. In other locations, where a higher density subgrade existed, such rill development was resisted by the SRG1 material.

It appeared possible to simulate the erosive effects observed in the laboratory and then have two controlled field sections whereby the lab results could be verified.

However, to do this the planned testing program would have to be significantly modified. The study team contacted ADOT and received approval to modify the testing program to incorporate the influence of overland flow.

Erosion Test Apparatus

To simulate the combined effects of precipitation and overland flow, an erosion cell was constructed. The main elements of the cell were a three panel bank which contained three replicated specimens of the material to be tested, and a overland flow simulator component. Each panel was 2.67 ft long in the slope dimension by 2.5 ft wide and allowed placing the material to a thickness of 2.5 inches. The slope of the panels could be varied to simulate any range of field slopes. The overland flow was delivered by 3 inch diameter ABS pipes which had been lined with Mirafi 6000 plastic placed with the extrusions up into the flow. The 6000 material was used to simulate field channel roughness and to increase the depth of flow prior to discharge onto the panels.

The overland flow pipes were constructed so as to allow their slope to vary, which in turn enabled the water discharge velocity to vary. The ability to vary the discharge velocity is important since the upper slope segments of field slopes vary widely, thus providing a corresponding variation in water velocity delivered to the lower slope segments. There was no way to measure overland flow velocities. The Mirafi 6000 material was intended to provide an approximation of these field channels thus enabling an estimate of the actual range of field flow velocities to be used in the testing. The velocity of discharge water is provided in Table 14.

The precipitation component of the fluid application was achieved by utilizing full cone spray heads located 50 inches vertically above the panel. Each spray head and each overland flow pipe had a flow meter. The flow meters insured that equal amounts of water were being applied to each of the replicated panels. Plates 4, 5 and 6 show the assembled erosion test cell.

The cell contains a sediment trap which is designed to hold all eroded particles greater than number 40 sieve size. The trap utilizes filter fabric to allow the water to leave the trap while holding the sediment back. The particles finer than the number 40 sieve size are not retained. To build traps large enough to contain all size particles is unnecessary and would have made the testing schedule impossible. The minus 40 material lost is estimated from the initial or pretest grain size curve and the particles larger than the number 40 sieve that were collected.

Table 14. Overland flow discharge velocities with quantity of flow Q

DISCHARGE QUANTITY (gpm)	SLOPE ANGLE (degrees)	VELOCITY (ft/min)
1.2	2	78
1.2	9	127
1.2	16	141
2.4	2	104
2.4	9	132
2.4	16	167

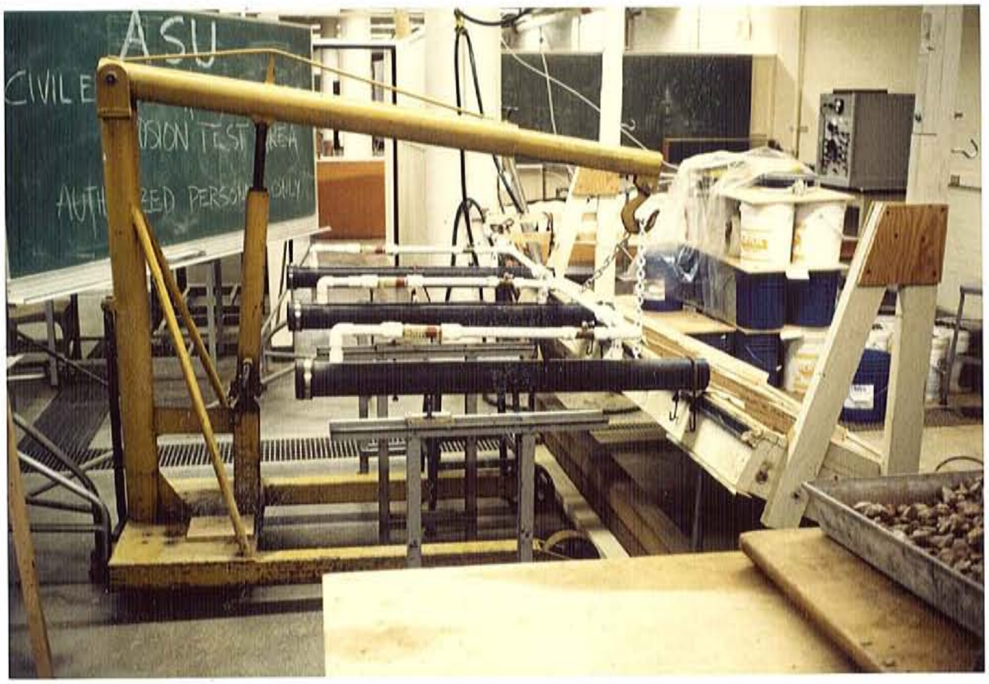

Plate 5. Side View of Erosion Test Cell

Plate 6. View of Spray Head and Flow Meter Assembly

To prevent sliding at the contact with the panel and the materials and to protect the test cell, Mirafi 6000 material was used to line the panel bottoms. At the lower end of the panel holding the material, holes covered with Mirafi 140N were used to allow subsurface flow similar to flow beneath the slope protection to occur without piping. This subsurface flow system also helped prevent artificially high pore pressures to develop.

The rate of water application to the panels to correspond to what will here after be referred to as "precipitation". It was determined by taking the predicted 50 year 30 minute intensity storm rainfall and dividing that amount of water by 30 minutes. This product was then multiplied by the spray area, which was approximately 22 inches in diameter, to determine the precipitation flux through the spray heads. The calculated amount of flow determined was 0.21 gpm. However, since the intensity varies widely during the design storm it was decided to increase the spray head flow rate to 0.5 gpm (1.9 L/min). At this higher flow rate a more severe erosion test resulted and the flow rate was more easily controlled thus insuring more reproducible test results.

The overland flow rates corresponded to the design storm precipitation falling on two microdrainages. The width of the drainages was established by reviewing the erosion channels produced along SR 360 by the storm of October, 1986. The spacing of rills was obtained from photographs taken after the storm and containing objects which enabled photo scale factors to be established. The examination of the slope rill spacing indicated that a microdrainage width of 3 feet should be used to calculate appropriate overland flow rates. The length of these drainages was established from reviewing the profiles of the slopes at the eroded sections. An example of a profile is given in Figure 2. Based on observed upper slope lengths, two lengths were used to determine the overland flows. Lengths of 15 feet and 30 feet were used in the calculations that produced 1.2 gpm (4.5 L/min) and 2.4 gpm (9.1 L/min). The graphs and discussions in the following section will refer to these flow rates.

In addition to the two standard flow rates, additional flows were used when the design flows did not produce slope distress. Flows as high as 8 gpm (30.3 L/min) were utilized for appropriate tests when additional information could be obtained.

<u>Typical Testing Operation</u>

A typical specimen testing operation would proceed as follows:

1. The sample location is selected.
2. The field sampling is done by removing 1200 to 2000 lb samples and transporting to the laboratory.
3. The sample is mixed to insure uniformity and then placed in the test cell.
4. When the material is being placed, the cell is at approximately 5 degrees slope. More material than is necessary is being placed on the three panels to allow for an as-placed

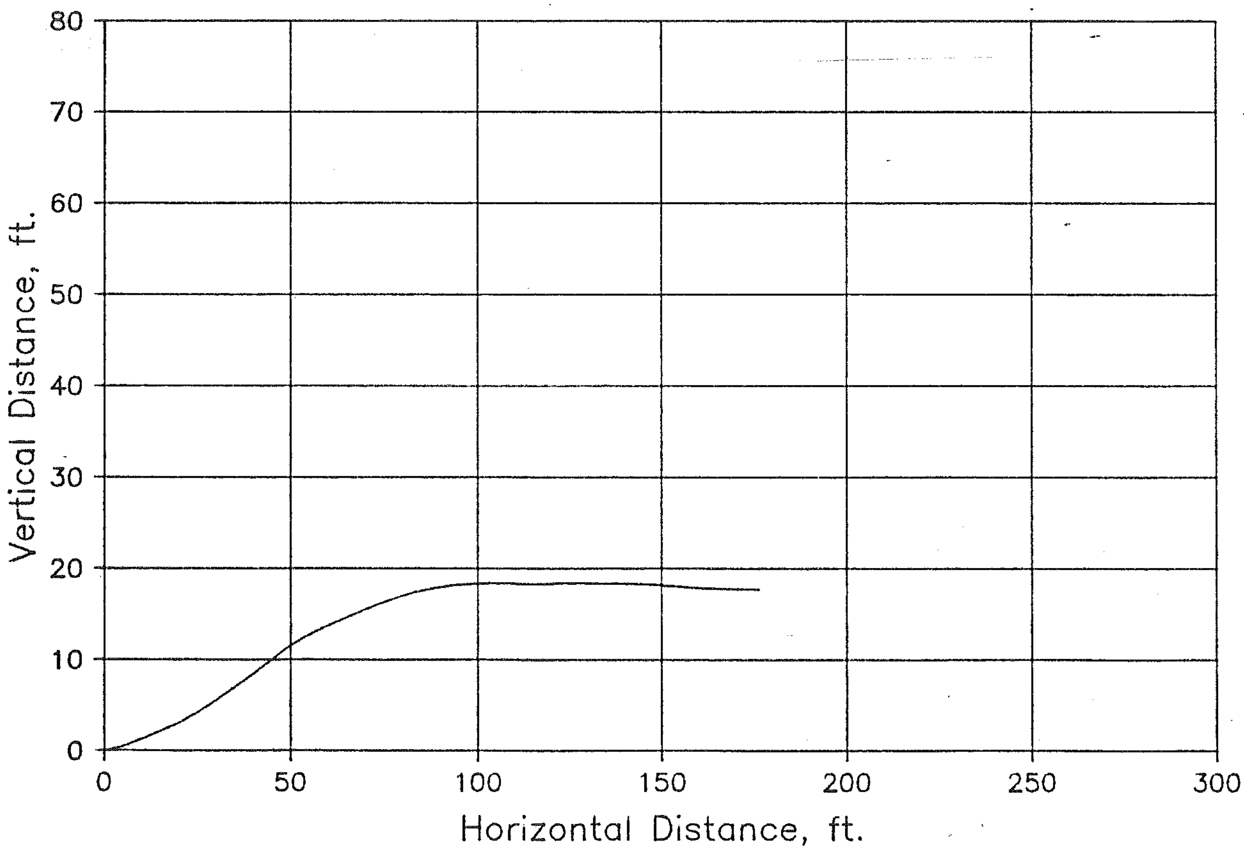

Figure 2. Profile of Slope West of Gilbert Rd. at Plate No. 2 Location

sample to be taken for grain size analysis. That sample is taken and the panel surfaces are leveled.

5. The panels are rolled with a custom built steel roller producing a line load of 110 lbs/ft of roller. This roller was selected as the best available simulator of construction and maintenance induced compaction on ADOT's slopes.
6. The cell is then brought to the proper test angle, generally at a 2:1 slope and locked into place.
7. The precipitation and overland flows have been preset and checked and test begins. Precipitation alone and then precipitation plus overland flow (combined flow) erosion test increments are run with care taken to insure that each panel functioned separately.
8. As the erosion test is running notes on the slope performance are kept. At the completion of a test interval the flows are stopped and the material eroded from each slope panel removed, panel by panel.
9. To facilitate the testing vacuum cleaners are used to remove the collected sample. Once collected, the sample from each panel is washed on the number 40 sieve and placed in the oven for drying and later grain size analysis.
10. Photos are taken to document the surface condition at the completion of the test and at other times when warranted.
11. The remaining material is then removed from the panels and the panels cleaned in preparation for the following test.

12. The material removed from the cell is transported from the laboratory.

13. The analysis of data begins.

Grain Size Analysis of Materials Tested

The materials selected for use in the erosion testing, either as is or as the basic material whose properties were modified, are shown in Table 15. The grain size curves for these materials are provided in Figures 3 through 14.

The initial testing operations, after the construction and calibration of the test cell were completed, involved examining several materials to establish their general response to the erosional environment. Approximately 10 tests or portions of tests were conducted during this early phase. As a result of the initial work it was apparent that several materials that were originally to be part of the testing program should be excluded. The most important exclusion from the testing program were slope protection materials from the Salt River channel. The initial testing comprised of three panels, showed these materials to be very well suited for slope protection against stresses caused by raindrop impact and overland flows greater than 8 gpm.

The Salt River materials were excluded from the production testing because they performed so well during the initial testing. The omission of these materials from the test program allowed the affect of particle shape on erosion to be made. The purpose of this phase of the testing was to establish basic erosional aspects of slopes and develop protective systems. As

Table 15. Summary of erosion test material properties.

SAMPLE ID	PERCENT PLUS #4	PERCENT MINUS #200	PI (a)
SRS1 (W/+ 1")	22	40	20
SRS1 (W/- 1")	13	32	20
SRG1	49	9	NP
SRP5	3	55	17
SRP5 W/ 10% SRG1	8	52	17
SRP5 W/ 30% SRG1	31	30	17
SRP5 W/10% IG1+20% SRG1	29	36	17
SRP5 W/20% IG1+20% SRG1	43	8	17
SRP5 W/ 30% Slate Creek	23	12	17
SRG8	72	0	NP
IP9	6	46	--
IG1	97	0	NP

(a) PI = plasticity index

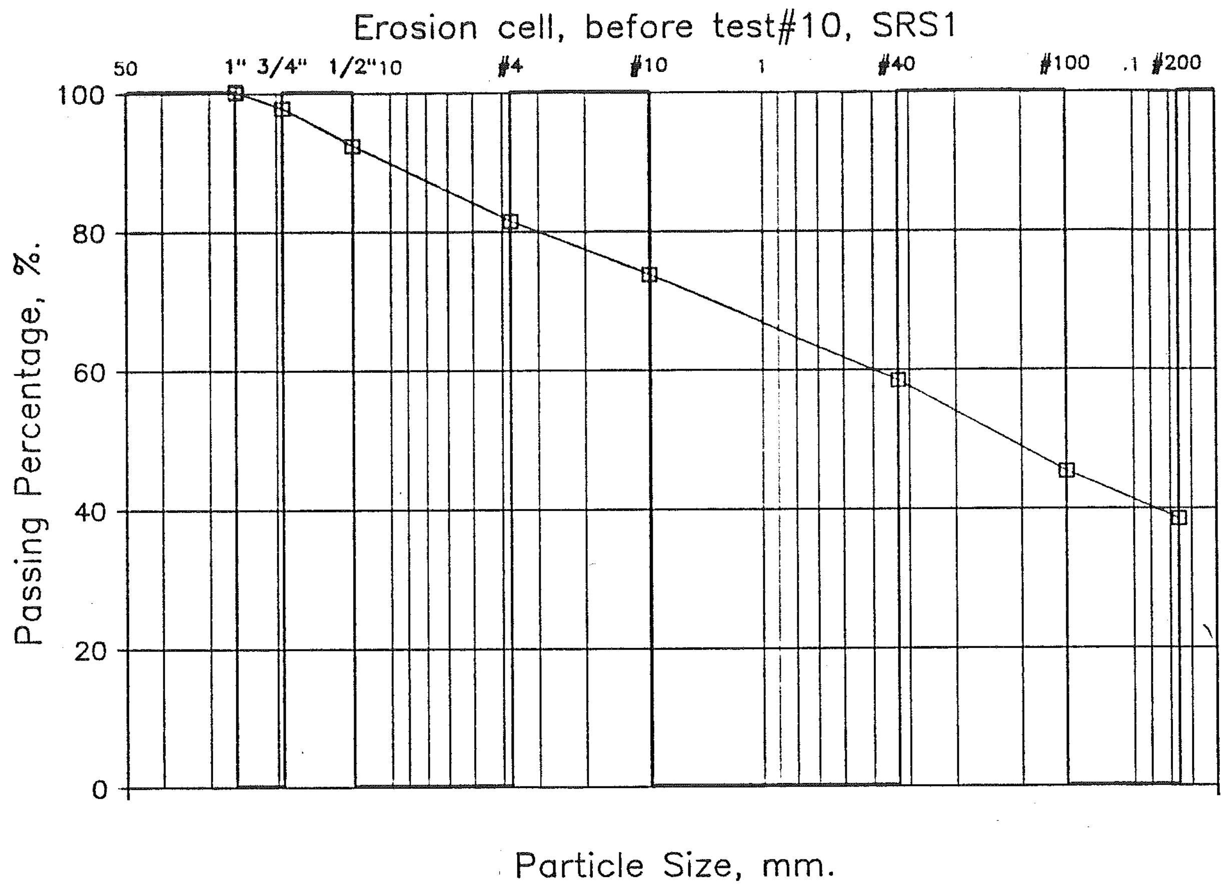

Figure 3. SRS1 Grain Size Analysis

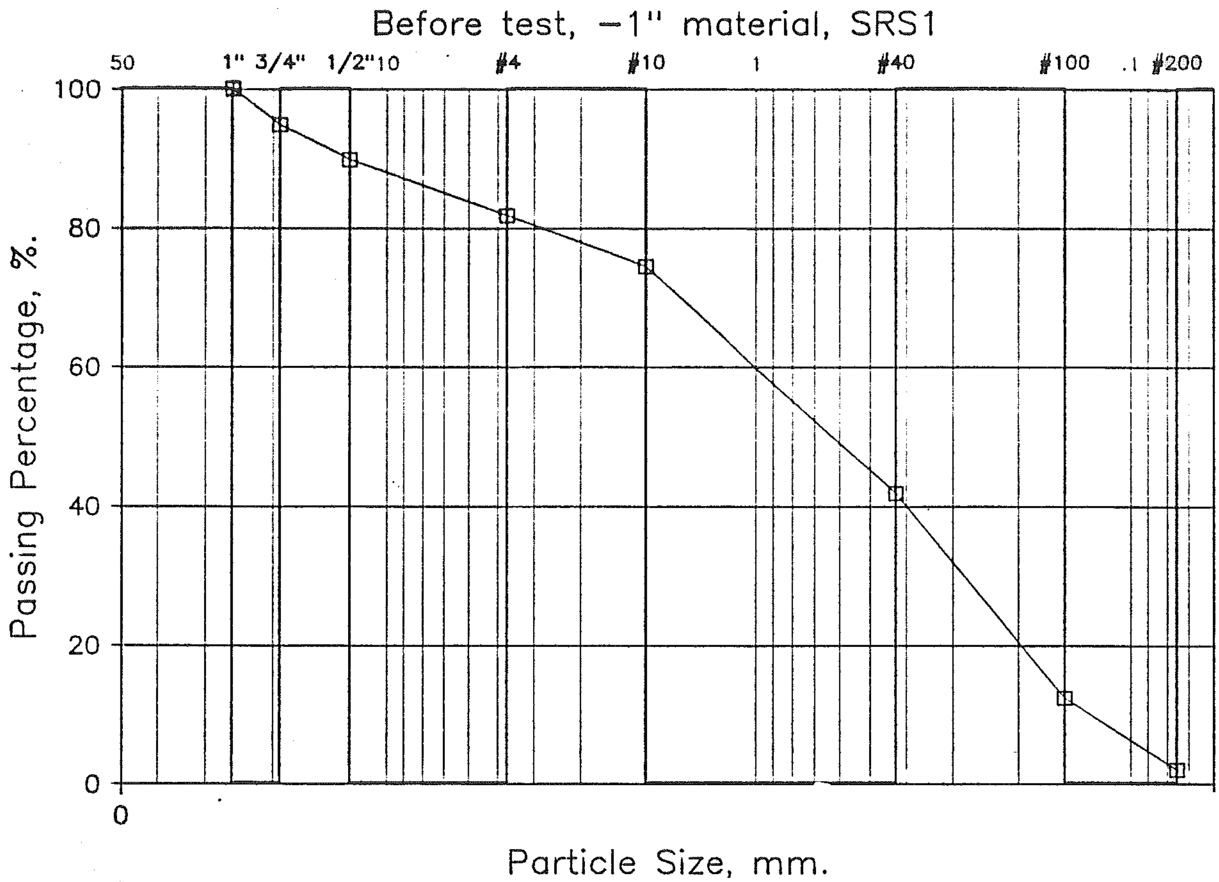

Figure 4. SRS1 - 1" Grain Size Analysis

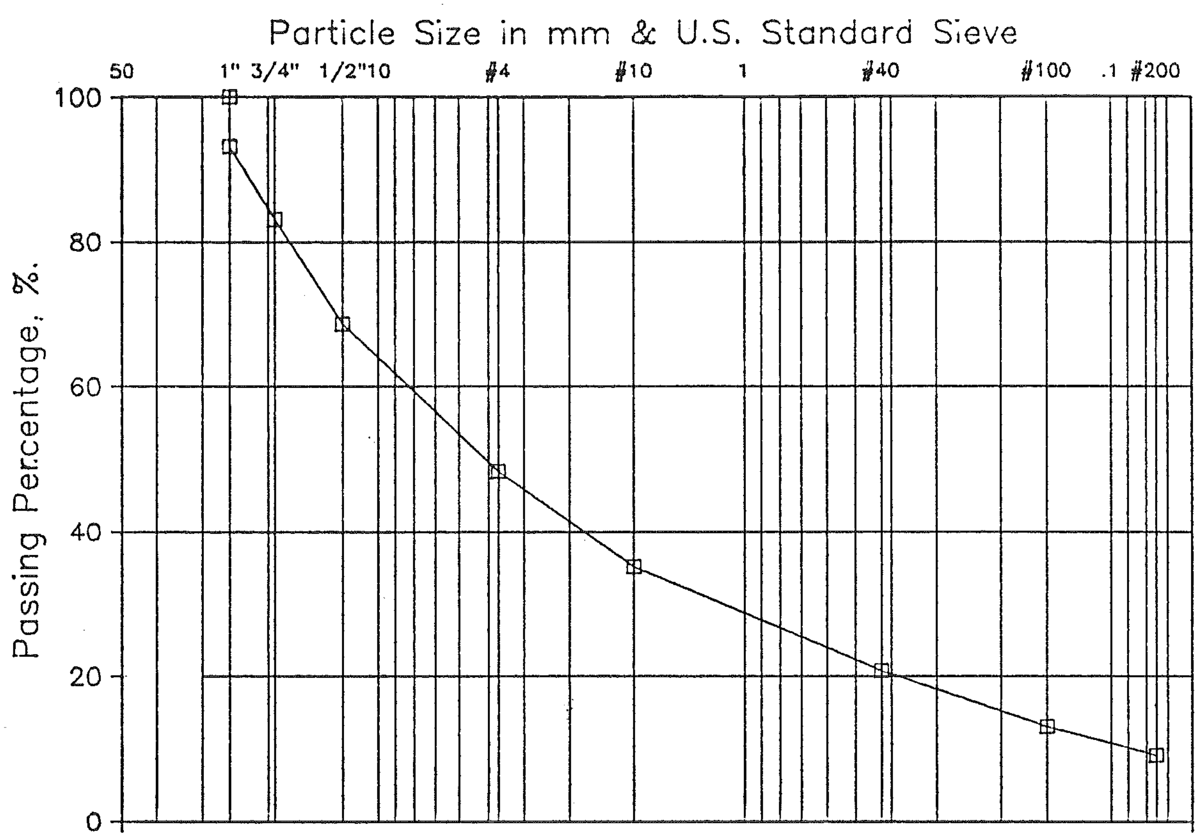

Figure 5. SRG1 Grain Size Analysis

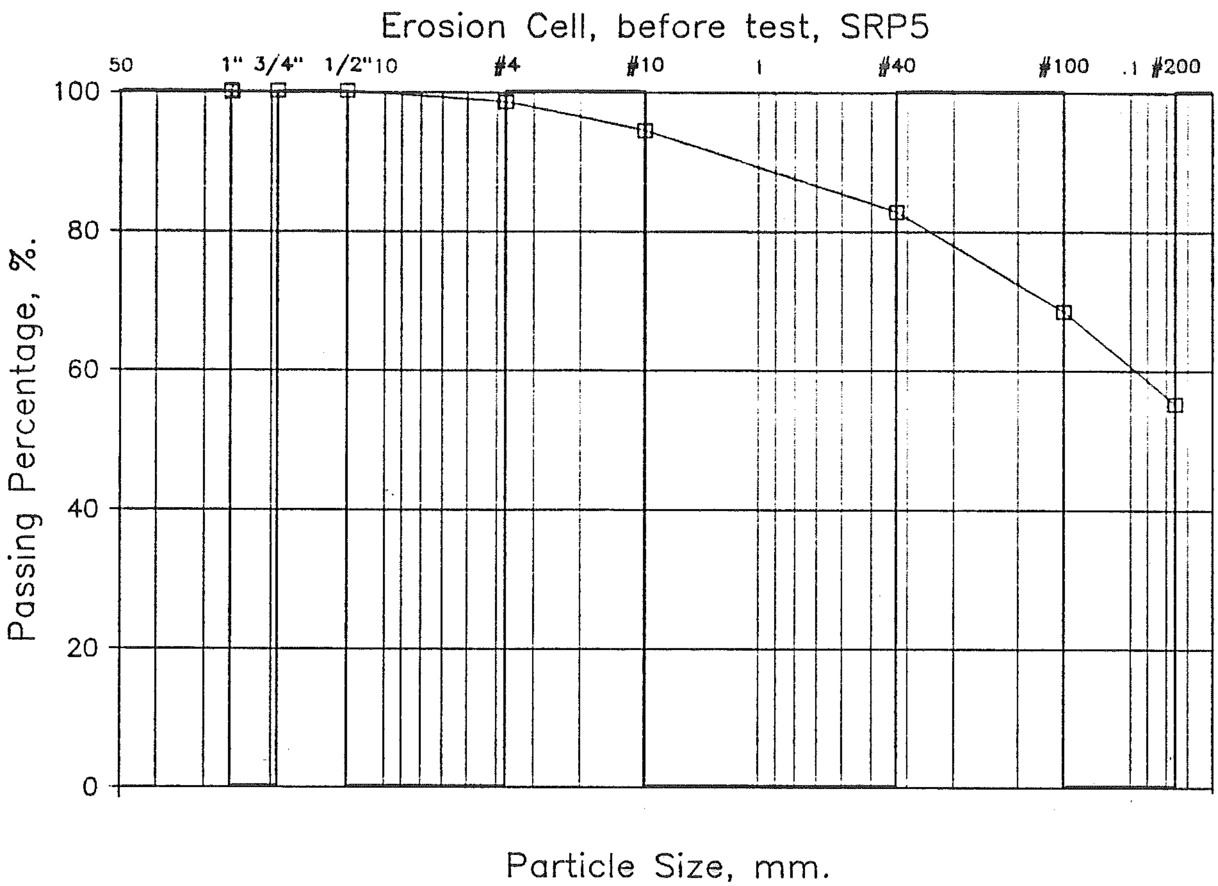

Figure 6. SRP5 Grain Size Analysis

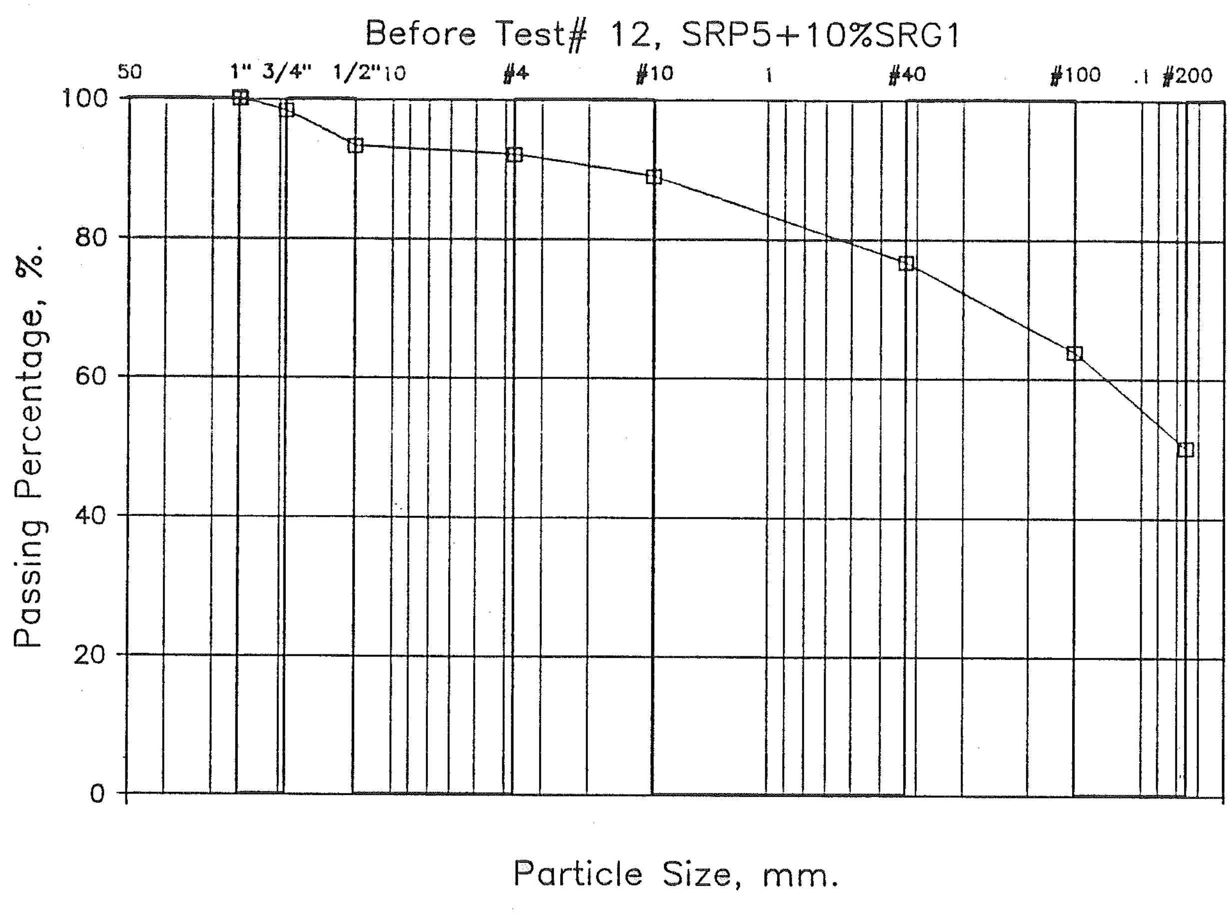

Figure 7. SRP5 Plus 10 % SRG1, Grain Size Analysis

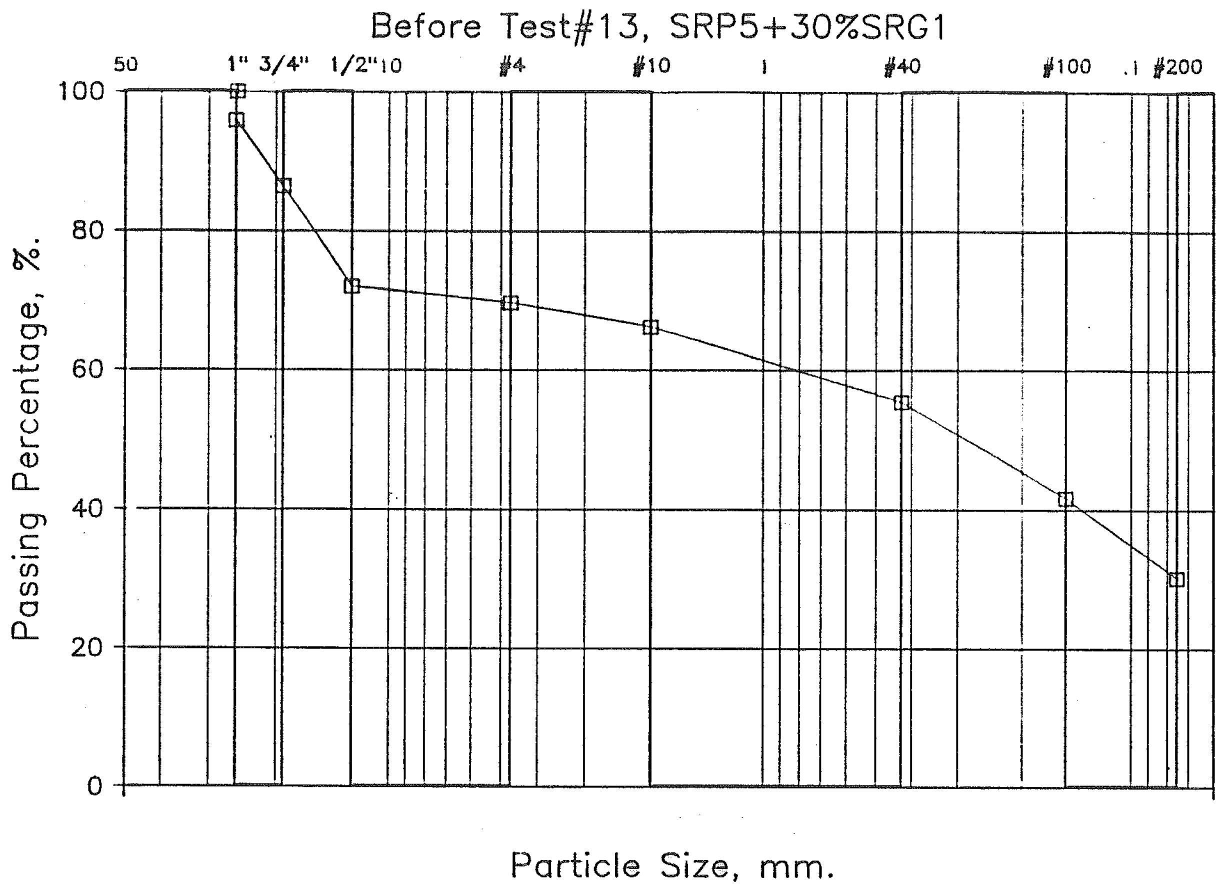

Figure 8. SRP5 Plus 30 % SRG1, Grain Size Analysis

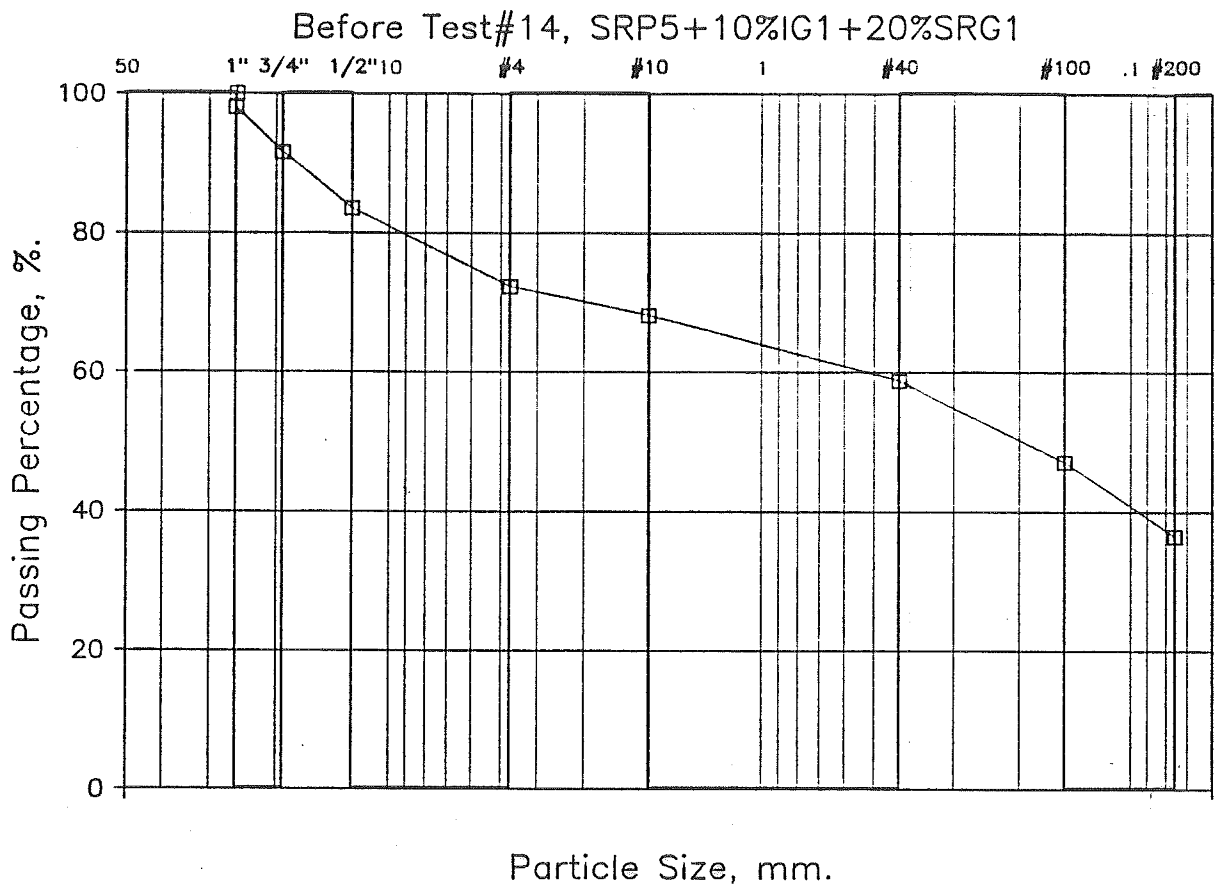

Figure 9. SRP5 Plus 10 % IG1 & 20 % SRG1, Grain Size Analysis

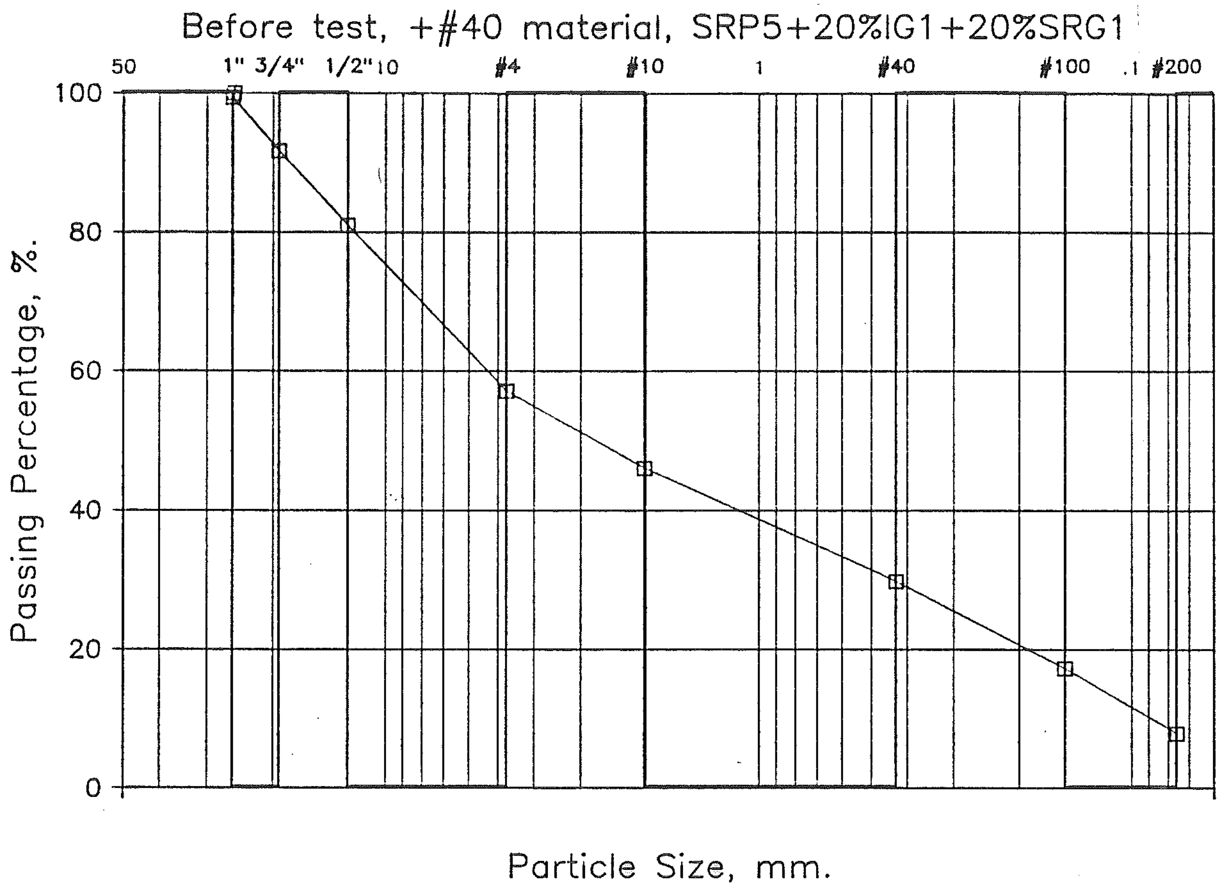

Figure 10. SRP5 Plus 20 % IG1 & 20 % SRG1, Grain Size Analysis

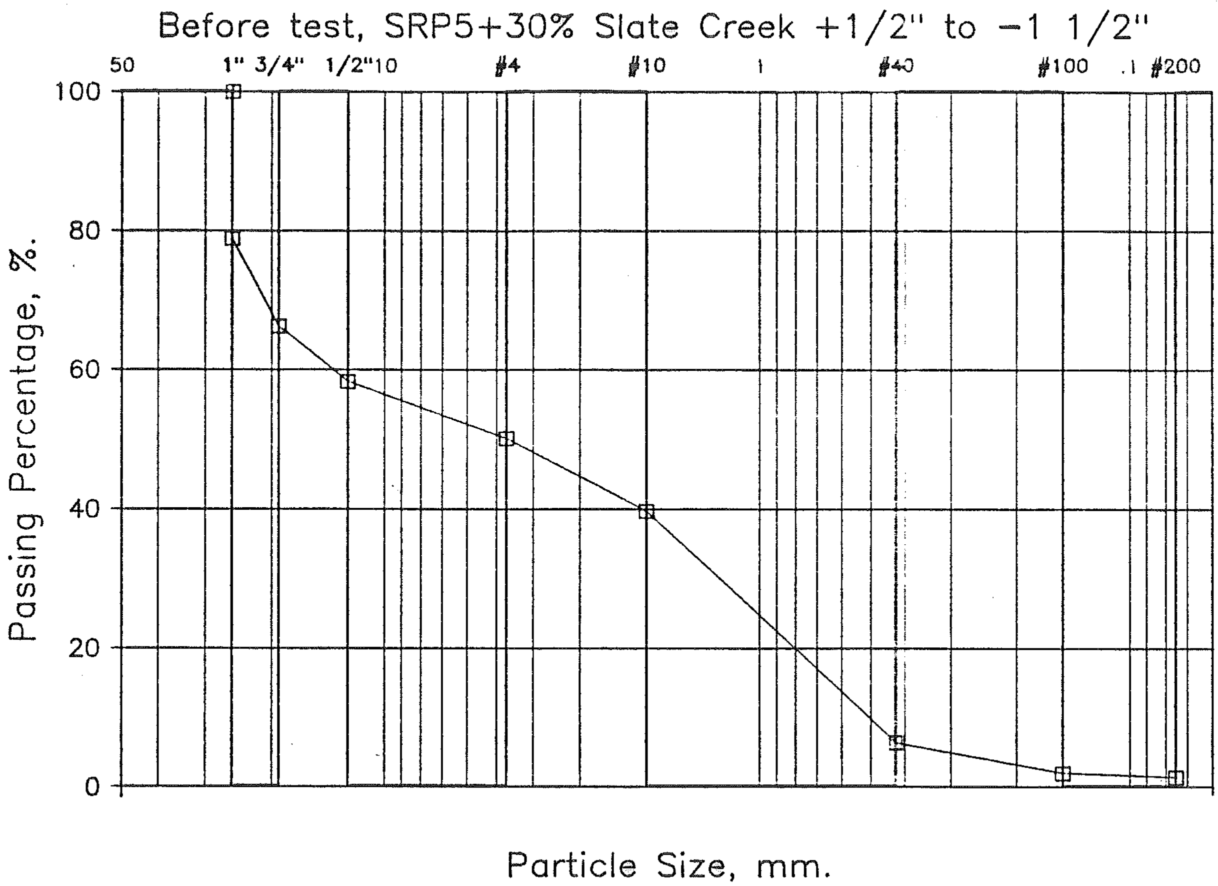

Figure 11. SRP5 Plus 30 % Slate Creek, Grain Size Analysis

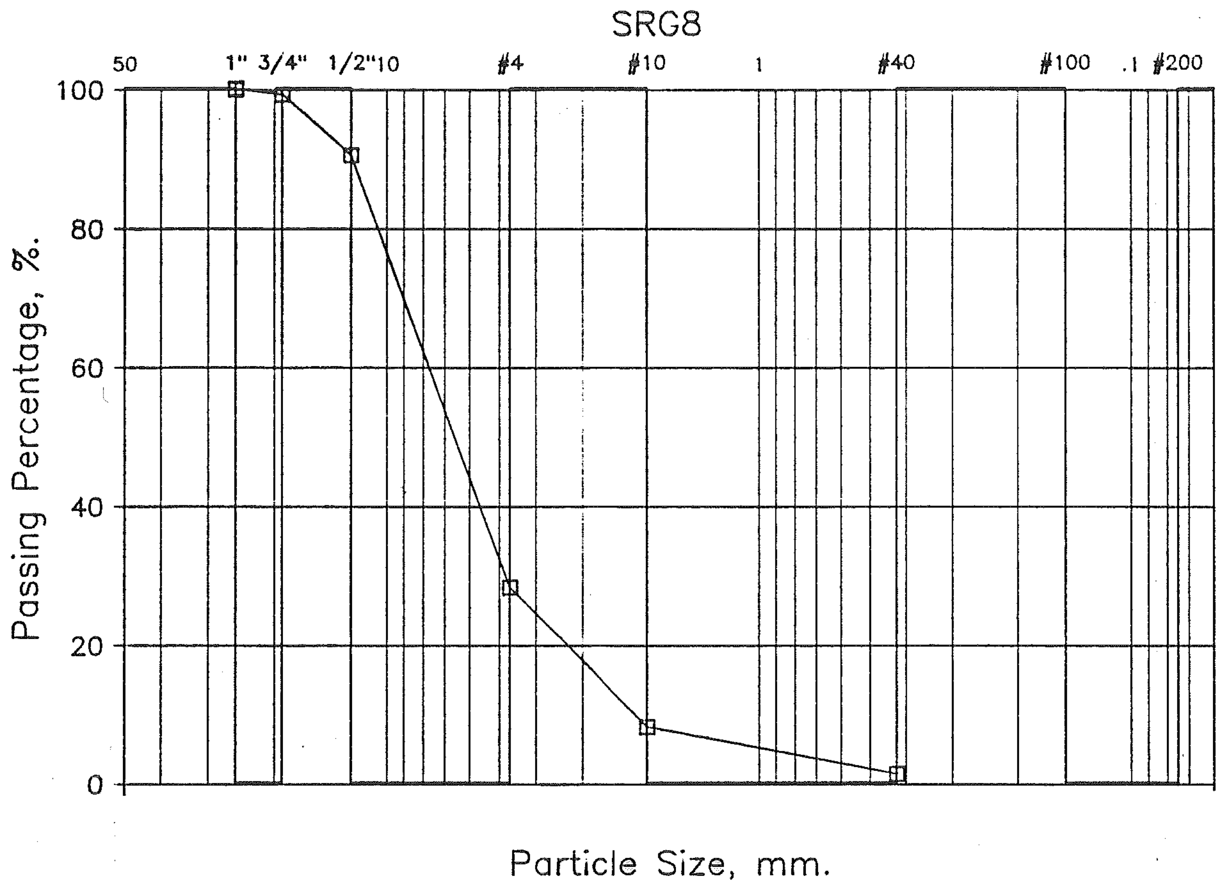

Figure 12. SRG8 Grain Size Analysis

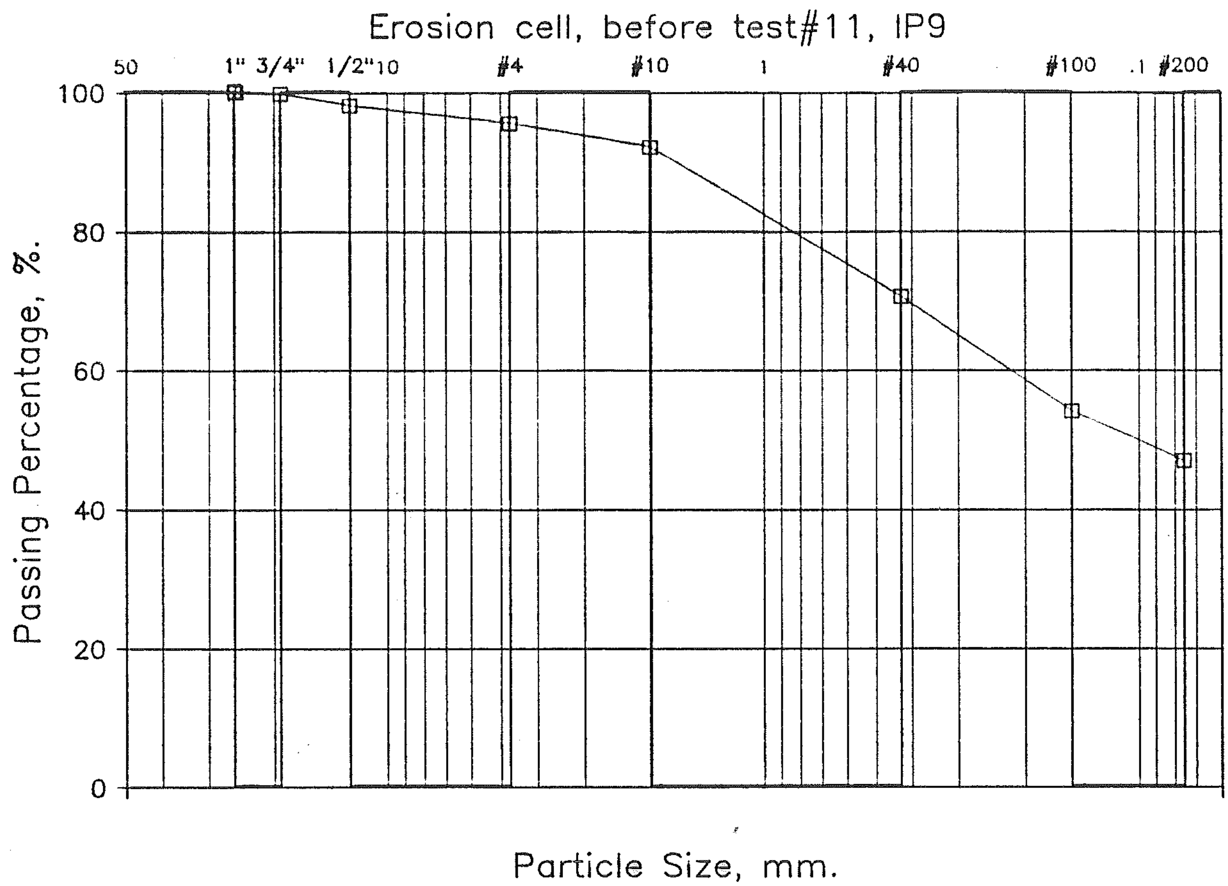

Figure 13. IP9 Grain Size Analysis

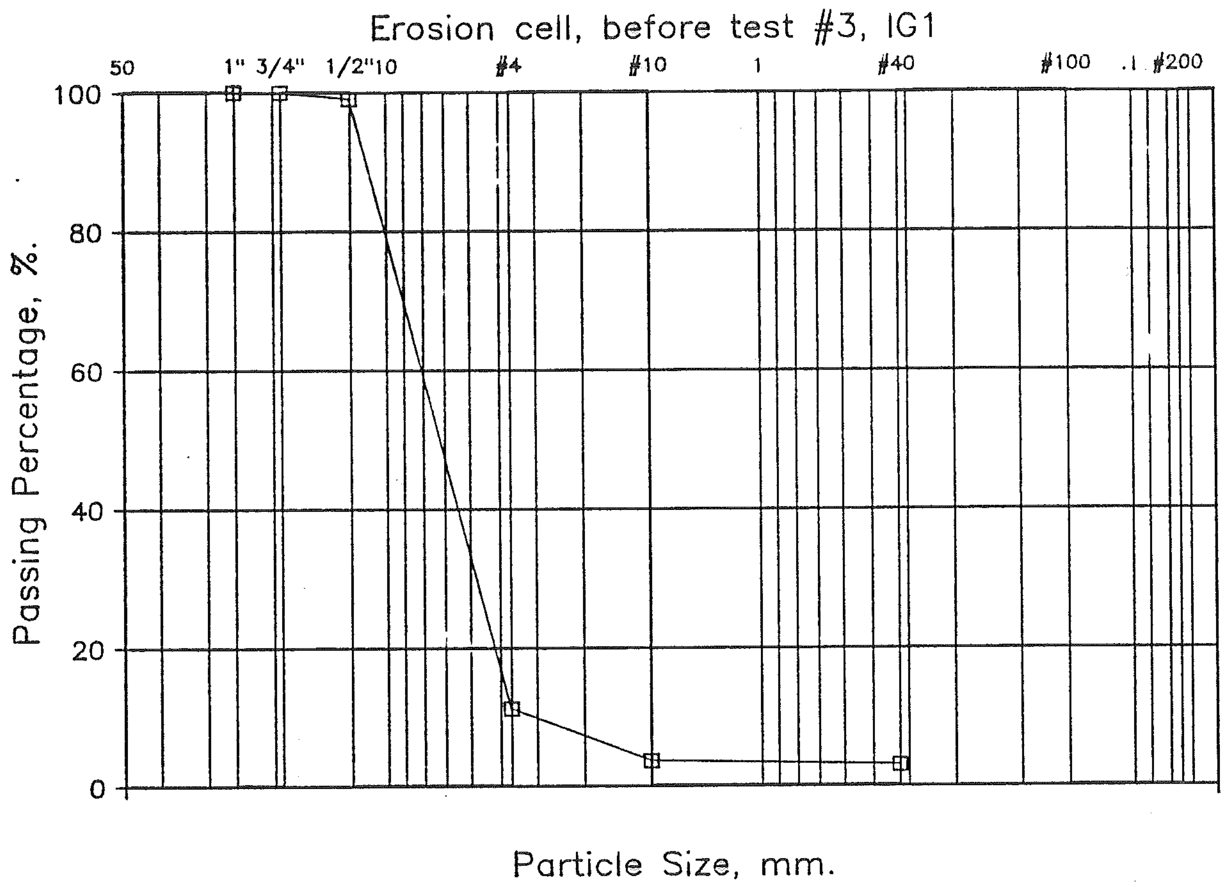

Figure 14. IG1 Grain Size Analysis

a result, a number of promising slope protection materials were not examined during this phase. It is hoped that in the future additional research can be directed to optimizing these materials for use as slope protection systems.

The initial testing also provided direction in refining the testing program by establishing the importance of surface permeability to slope protection. The early results demonstrated that materials with a very poor actual slope performance fared extremely well during testing, the SRG8 and IG1 granites in particular. These materials had very high permeabilities, so high in fact that they did not support surface flow even during the maximum flow test. The observation of this phenomenon alerted the research team to the need to consider the long term permeability of protection systems. In addition to incorporating long term permeability testing into the research program, the interaction between thin surface protection systems and the underlying soils was also explored.

Another observation that assisted in focusing the testing program was the role surface density played in erosion resistance. The initial testing made it clear, that (for soils similar to the plating soils used on SR 360 and I-10, some densification is essential). After soils from these highways were spread on the panels and leveled they eroded so badly at the initiation of the testing that further testing was pointless. As a result of these observations, the research team used a uniform placement density that simulated actual field placement conditions. Later research can explore the density versus resistance relationships for a wide suite of materials. However, it is clear at present that smooth and dense surfaces are necessary to mobilize erosion resistance when soils with fines are present.

The initial testing also indicated that the testing program should concentrate on testing at the steeper slope range. The erosion relationships are so complex, that the researcher needs to know what works at the upper limit of design slopes, the early observations showed that the severity of erosion increased from 22 degree slopes to 27 degree slopes and that some materials were stable at the lower slope but suffered channel erosion at the higher angle. The testing operations focused on the 2:1 slopes (approximately 27 degrees) because it was apparent that what would benefit the steeper slopes would benefit the lower ones. Erosion would occur at the lower slopes but at a less rapid rate. Further research should be directed at exploring the slope-erosion resistance relationship for a variety of materials and slope protection systems.

The initial erosion testing also made it clear that small amounts of coarse particles (the plus no. 4 size fractions) could produce big returns in reduced erosion. The study team expanded this aspect of the testing because of the potential advantages possible in minimizing slope protection costs.

The early testing also provided an indication that the design overland flows would not be high enough to produce channel or rill failures with some materials. The program was expanded to incorporate flows larger than designed to assess the upper limit of material resistance. Though the test times were increased by this step, the information gained was valuable.

A point of concern to the study team was the dimensions of the panels and the manner in which the overland flow was simulated. There was a concern that the panels were not long enough and that the overland pipes may create too much local damage and invalidate the results. The early tests were examined closely with respect to these concerns. Both concerns were dispelled after the first four test panels were tested. Erosion channels similar to those found in the field were developed in the laboratory. During the erosion testing results were reviewed to insure that good correlation with field observations were realized. This included the observation of rills starting at mid panel. The occurrence of rills starting at mid slope, slope break point, were documented at SR 360 west of Gilbert Rd. following the storms of February 1987 plates 1 and 2 in volume II. The study team was satisfied that an adequate representation of field induced erosion was possible and obtained in the erosion test cell.

Discussion of Test Results

The production testing began once the initial examination of material response to erosion was completed. the SRG1 material from west of Val Vista Rd. on SR 360 provided some useful information concerning how soil with a coarse fraction can develop increased erosion resistance through armoring. This material had 51 percent plus number 4 size material prior to erosion testing. The results of the initial testing of SRG1 are shown on Figure 15. The precipitation only erosion increased to a maximum value 10 minutes into the test and then continually decreased to a minimum value at 40 minutes.

The reason for the initial increase in the rate of erosion is believed to be caused by surface irregularities left after panel preparation and "poorly" placed coarser particles which are in rather unstable positions at the start of precipitation.

The erosion rates are the averages of the three test panels. Three panels were utilized since it was recognized that although great effort was taken to make the three panels identical, variations would occur. The researchers felt that three replicates were the minimum number necessary to comply with project scope. The erosion rate was determined by dividing the total weight of the plus number 40 material collected by the duration in minutes. To determine the total amount of material eroded the rates for each time increment must be multiplied by the time and summed. At the completion of the 40 minute test increment the SRG1 soil had developed an effective surface armor comprised of primarily plus number 4 particles. In fact what was observed in the laboratory was a high initial loss of fines followed by steadily decreasing sediment transport from the panel. The sample of the plus number 40 material from panels 1 and 2 after 10 minutes of testing was combined and the grain size established, (Figure 16). The sample collected was 99 percent finer than the number 4 sieve and 57 percent finer than the number 10 sieve size. The grain size analysis for the similar samples collected at 30 and 40 minutes into the test;

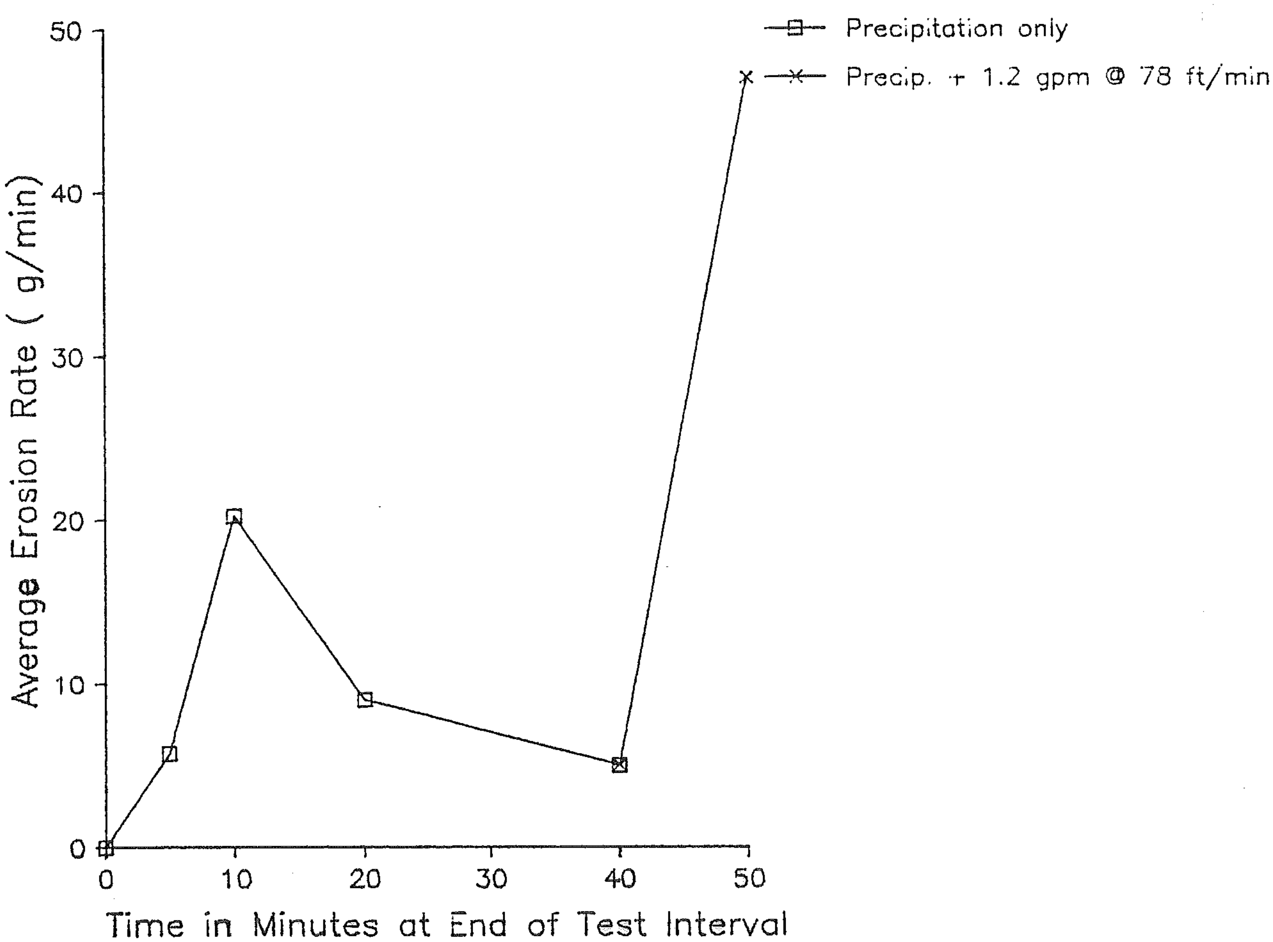

Figure 15. SRG1 Erosion Vs. Time, Combined Flow Conditions, for 2:1 Slope

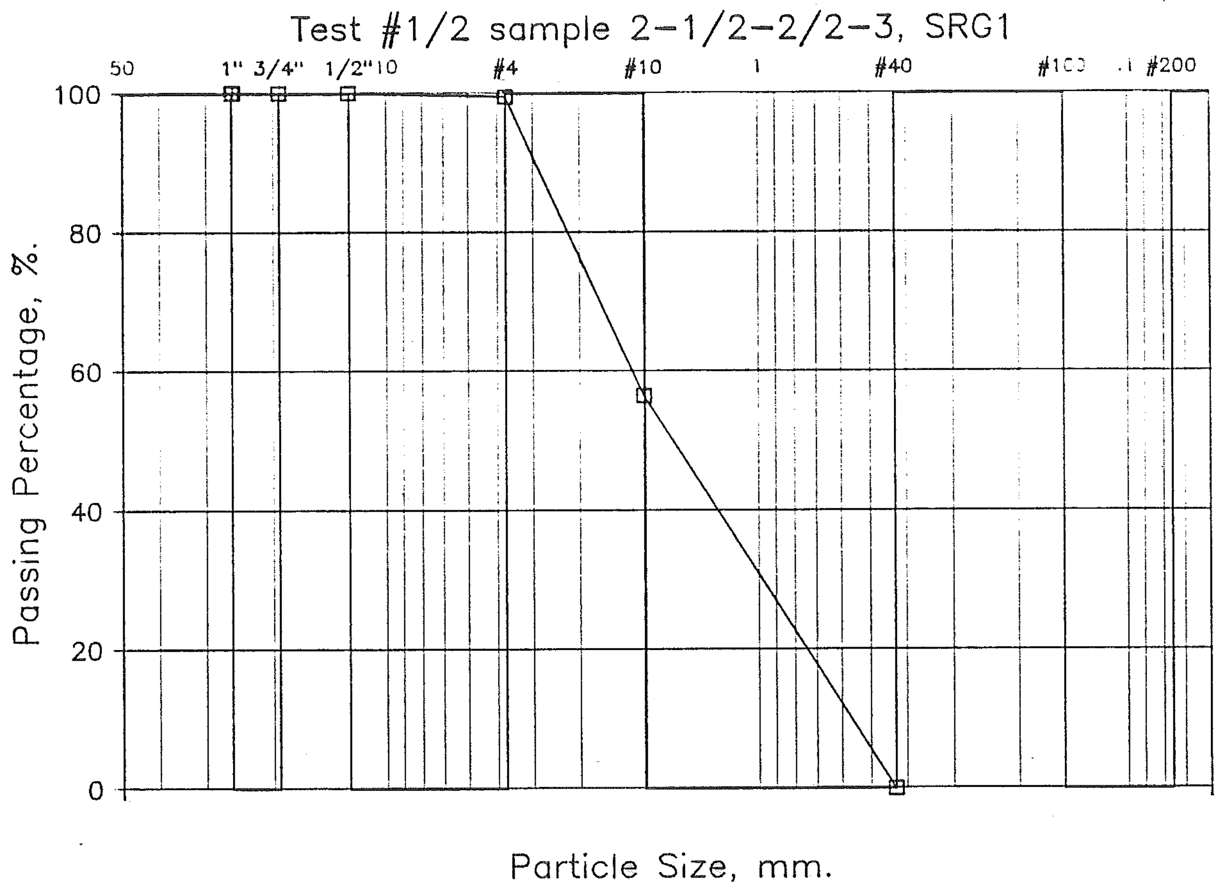

Figure 16. SRG1 Grain Size Analysis after 10 Minutes of Precipitation Induced Erosion

Figures 17 and 18 show similar results. These data show that it is the minus number 4 sieve size particles that are transported by precipitation alone.

Another interesting observation apparent when Figure 18 is examined concerns the relatively steady state processes at work on the soil face. The percentage of plus number 4 size particles collected increased from 0 at 30 minutes to approximately 5 percent at the end of 40 minutes. While very small, this increase in the plus number 4 size particles is to be expected as the slope continues to be stressed by the precipitation. As long as fines continue to be removed the coarse particles will be shifting into more stable positions. The fact that these coarse particles are in motion provides some particles sufficient movement to be transported from the panel. This soil is so efficient at developing protection by the armoring process plus number 4 size particles involved in large movements are few.

The fact that the precipitation portion of the SRG1 test eroded essentially fine particles is interesting because the storm of October, 1986 produced the closure of SR 360 in the vicinity of the sample source for SRG1. The freeway was closed due to water and "mud" on the road. The transport of fines from the first rain after placement of the SRG1 material was predicted by the laboratory test.

Overland flow was started at the completion of 40 minutes of precipitation for the SRG1 material. There was a dramatic increase in the rate of erosion as the combined effect of pre-

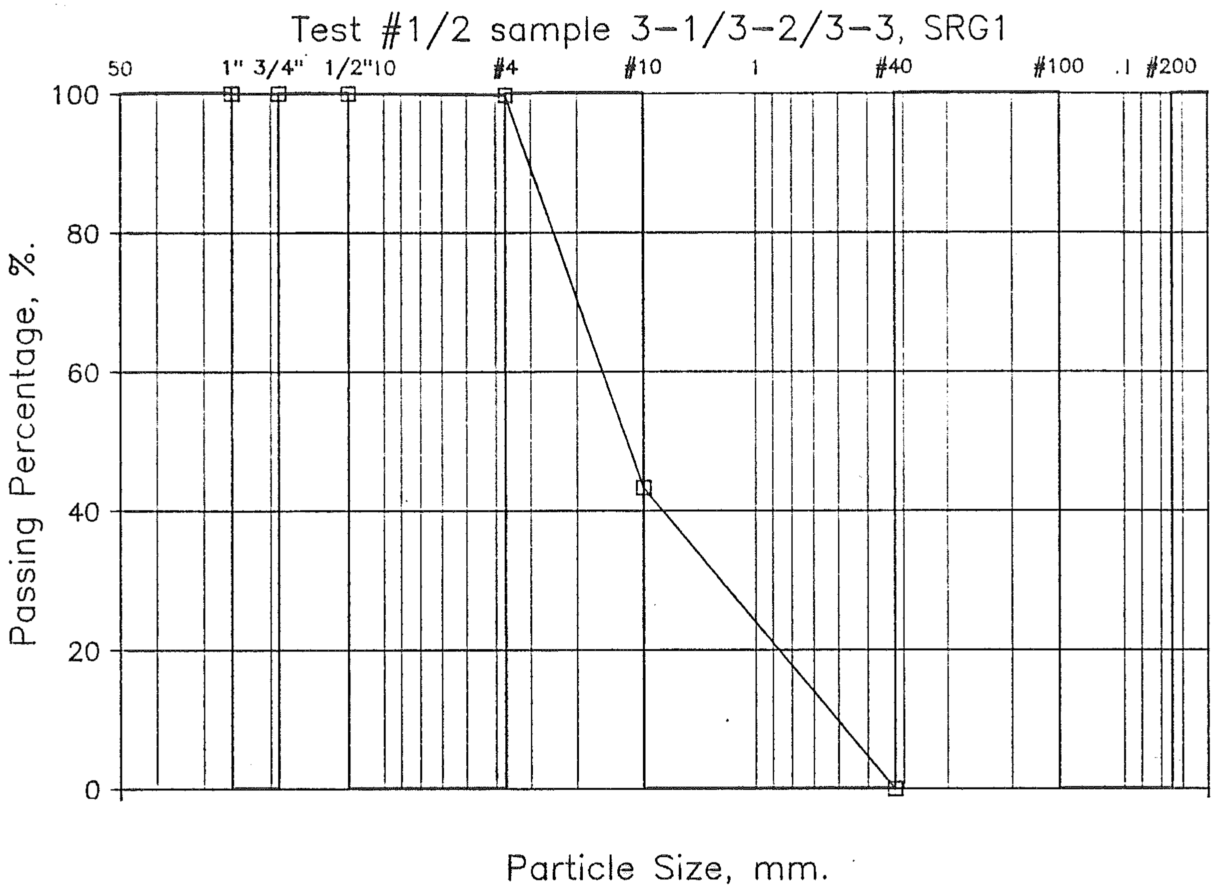

Figure 17. SRG1 Grain Size Analysis after 20 Minutes of Precipitation Induced Erosion

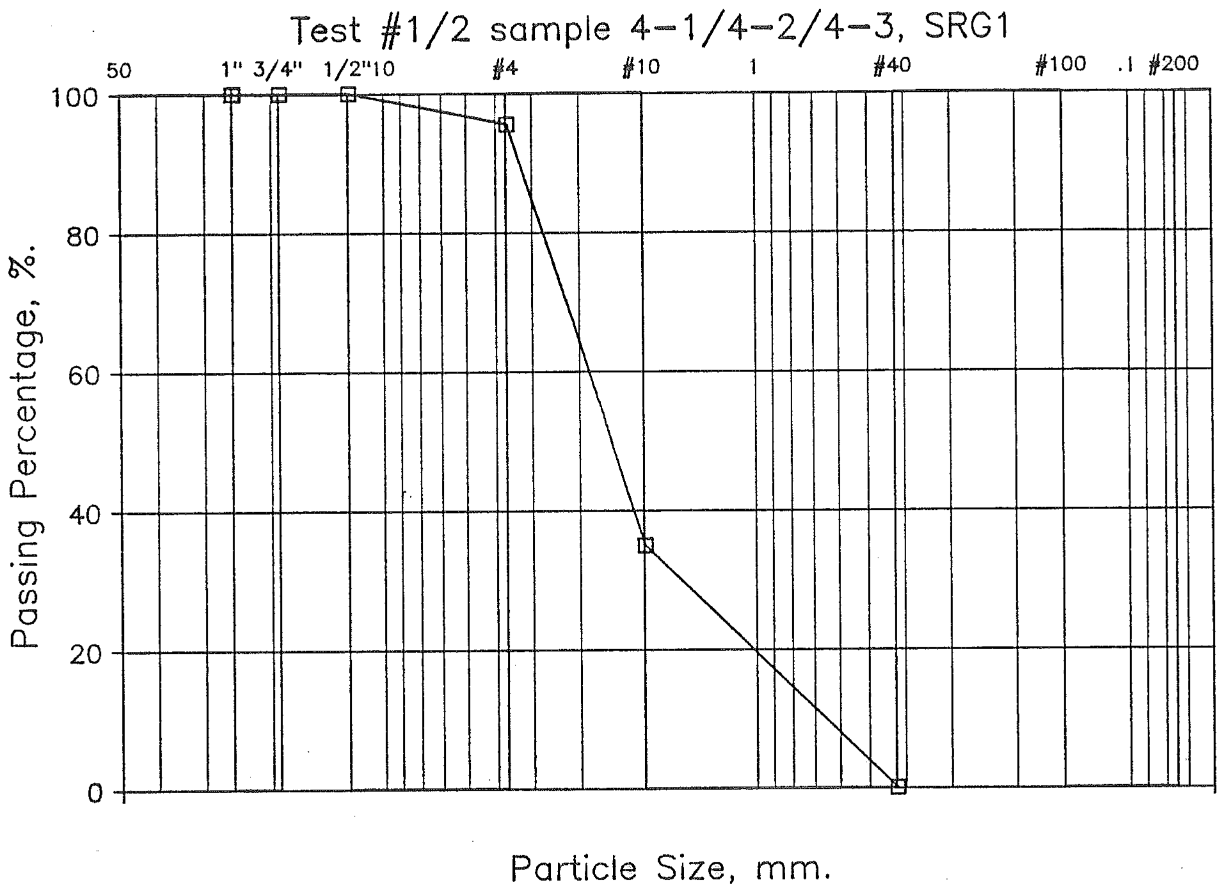

Figure 18. SRG1 Grain Size Analysis after 40 Minutes of Precipitation Induced Erosion

cipitation and overland flow was felt, (Figure 15). Even after 40 minutes of previous testing the erosion rate more than doubled. This increase in erosion occurred as particles which had been stable under the previous flow regime proved unstable under the new one. Figure 15 makes it clear that any erosion prediction must consider the overland contribution if the true material erosion resistance is to be predicted.

The cumulated samples of the panels after 10 minutes of the combined flows still had 88 percent of the plus number 40 material finer than the number 4 sieve size (Figure 19). It is apparent that under the added stress of the 1.2 gpm flow the plus number 4 particles are relatively stable. These coarse particles are able to develop new armor at the slope surface.

At the completion of the initial 10 minutes of flow with both precipitation and overland flow applied, the combined flow testing was continued for SRG1. The flow volume of 1.2 gpm was continued but the overland flow velocity was increased to 141 ft/min (43.0 m/min). The rate of erosion versus time for this additional testing is provided on Figure 20.

When Figures 20 and 15 are compared it is apparent that when testing started with the same flow but at a higher velocity, the erosion rate increased. However, the armoring associated with the overland flow of 1.2 gpm and 78 ft/min was considerable. The rate of erosion of approximately 47 g/min associated with the first overland flow after 10 minutes is approximately 5 times greater than the rate of erosion for the second interval, with a velocity of 141 ft/min, after the same time

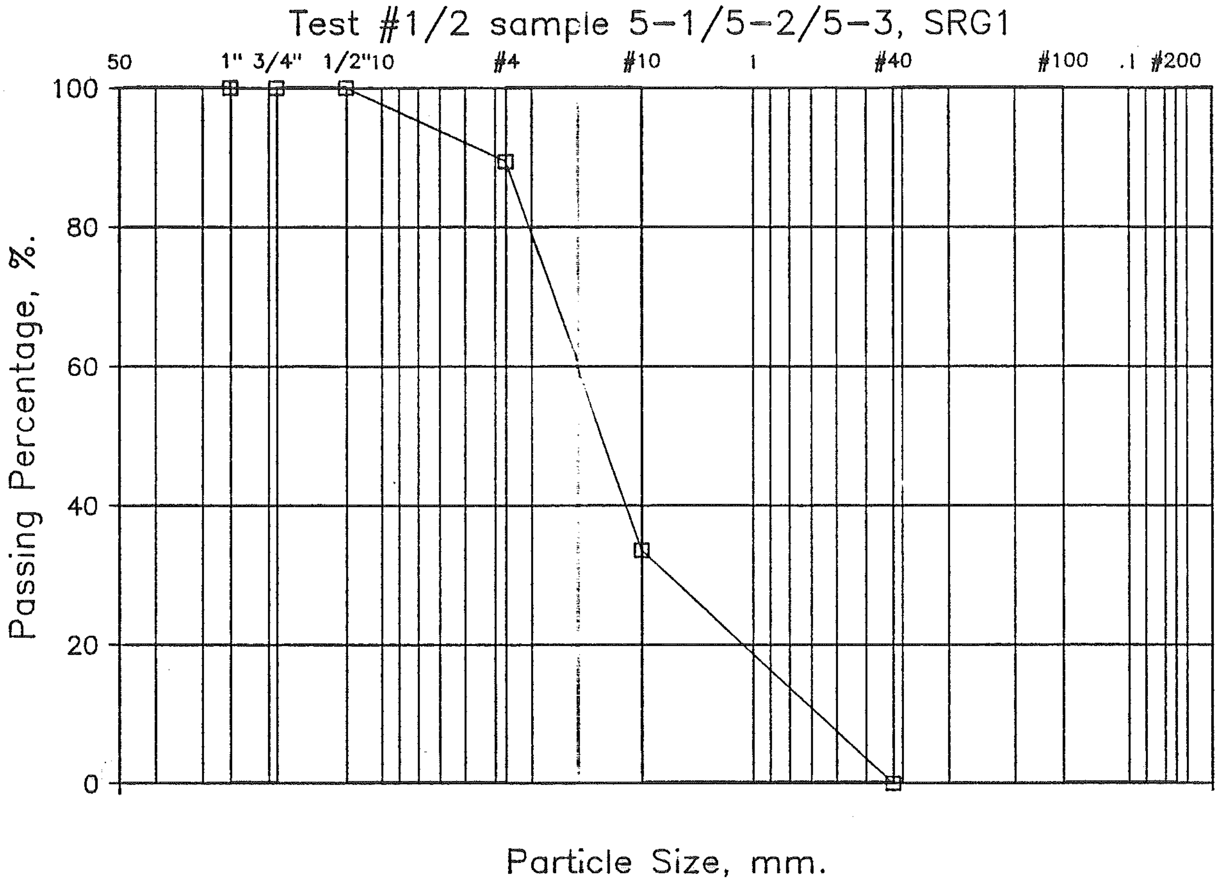

Figure 19. SRG1 Grain Size Analysis after 50 Minutes of Precipitation and 10 Minutes of Overland Flow

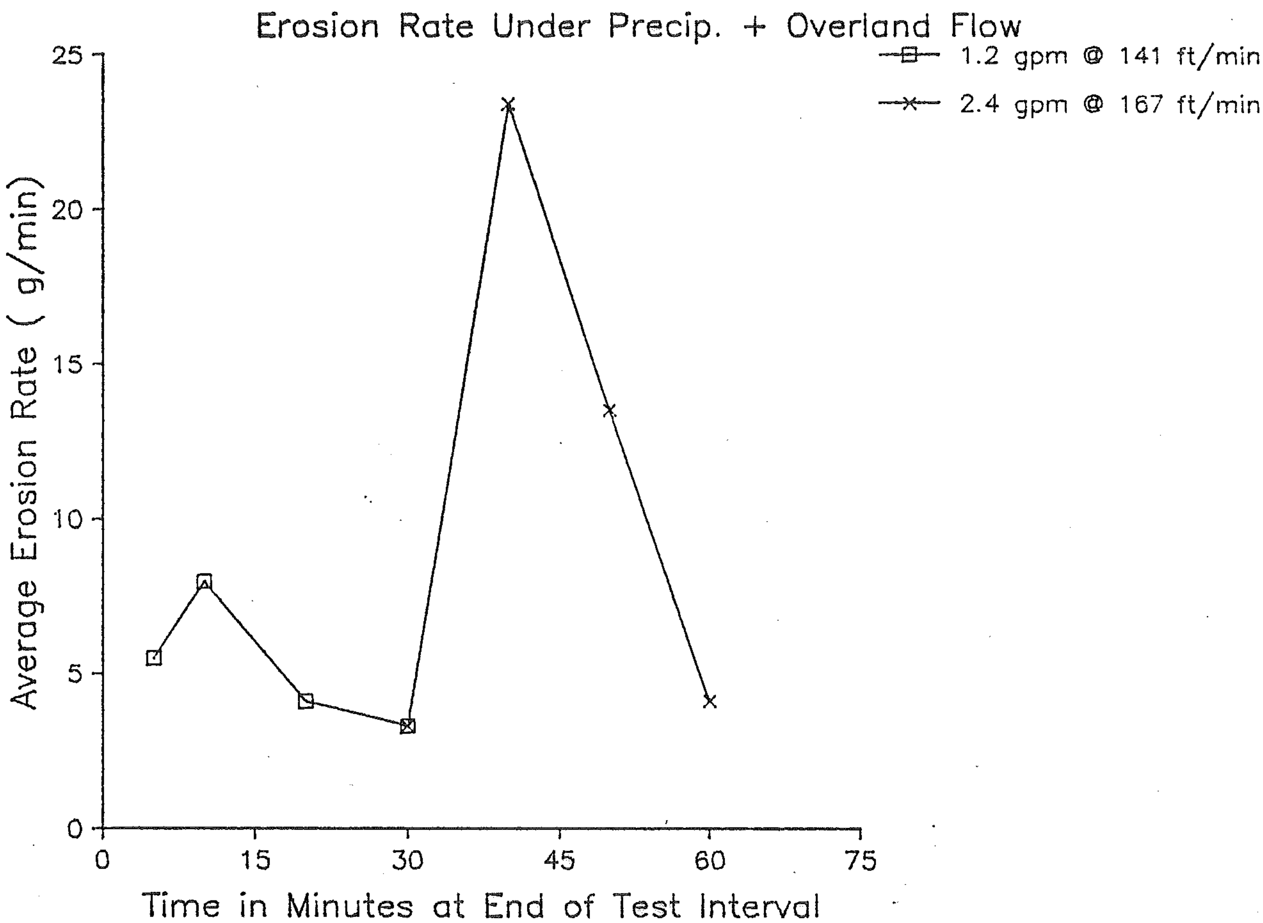

Figure 20. SRG1 Erosion Vs. Time for 2:1 slope
and Q = 1.2 & 2.4 gpm (4.5 & 9.1 L/min)

had passed. The erosion process continued, but the rate of erosion decreased rapidly.

The reason for the increase in the rate of erosion shown on Figure 20 between 5 and 10 minutes is believed to again be the initial relocation of some coarse particles. When the velocity of flow increased by over 80 percent, some particles were unable to resist the new flow environment without an adjustment in position. The combined samples of the plus number 40 material eroded after 10 minutes at the higher velocity flow were 95 percent finer than the number 4 sieve size. (Figure 21). Not only does the slope continue to armor, as demonstrated by the reduction in the rate of erosion, but primarily the transport of particles smaller than the number 4 sieve size continues.

As flow at the velocity of 141 ft/min continued the rate of erosion continued to decrease for the following two 10 minute test intervals, (Figure 20). The rate of erosion decreases from 8.0 to 3.3 g/min over the 10 minute to 30 minute test periods.

After 30 minutes of testing at the 1.2 gpm and 141 ft/min flow rates was completed the flow was increased. The volume was increased to 2.4 gpm and the flow velocity increased to 167 ft/min (50.9 m/min). The rate of erosion for the next 10 minute test interval increased to 23.4 g/min, (Figure 20). At this more severe erosion condition the percentage of plus number 4 size particles that were eroded increased to 27 percent of the collected combined sample (Figure 22).

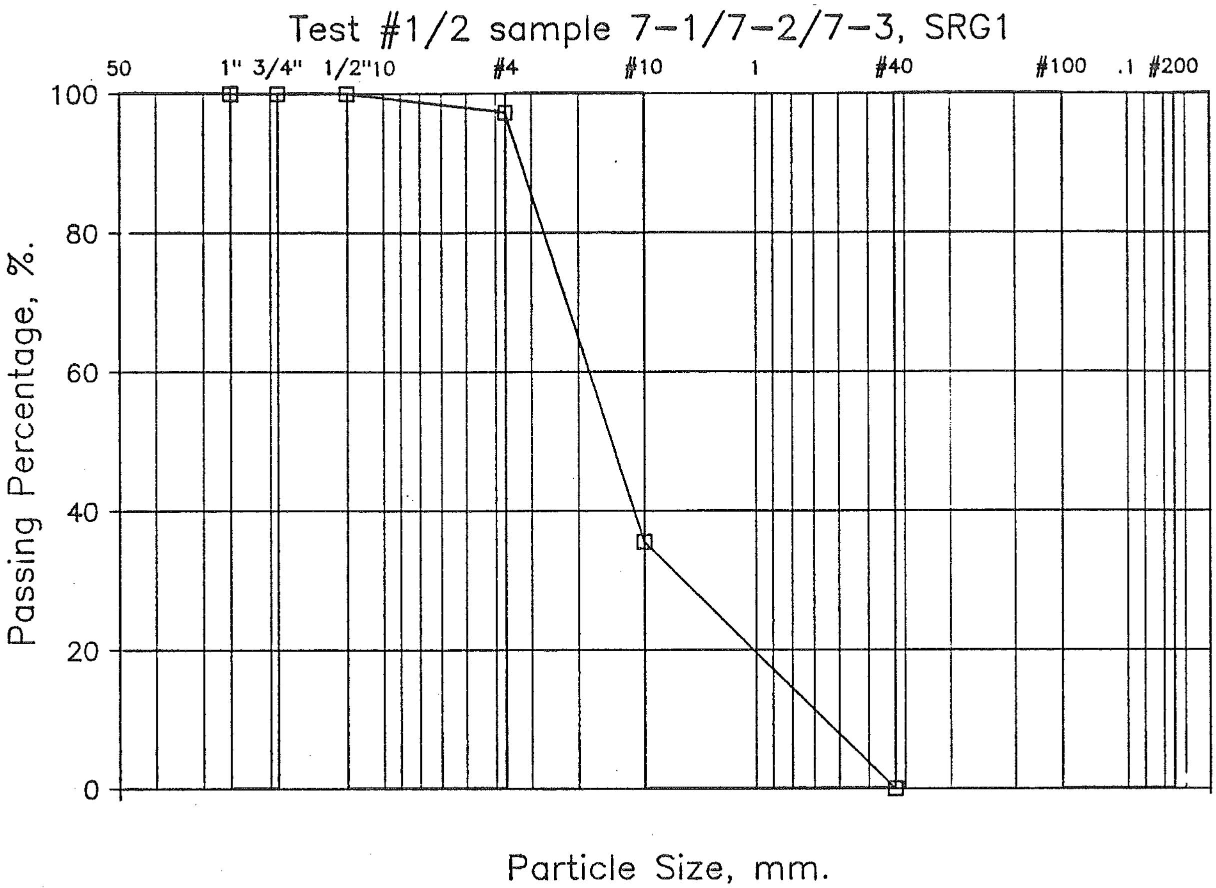

Figure 21. SRG1 Grain Size Analysis after 10 Minutes of Combined Flows of 1.2 and 2.4 gpm (4.5 & 9.1 L/min)

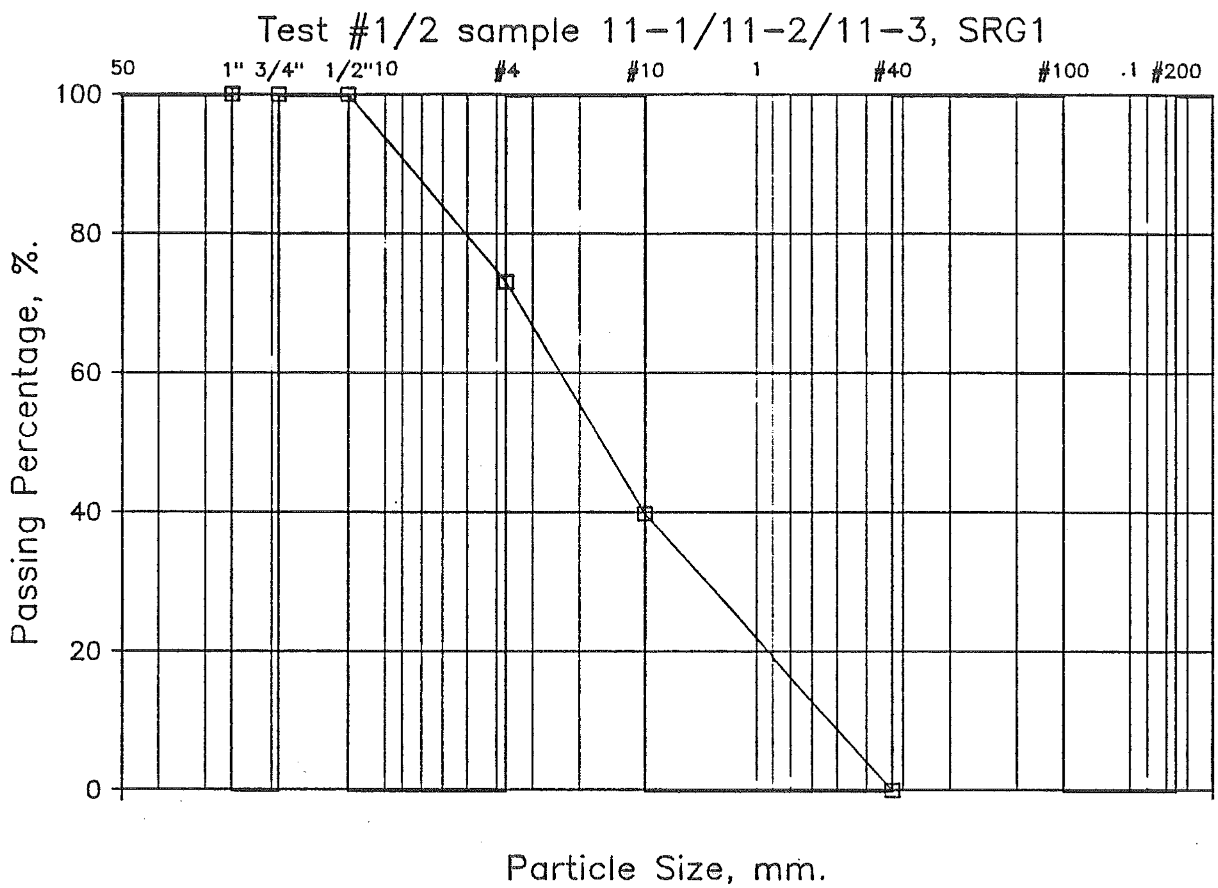

Figure 22. SRG1 Grain Size Analysis, 10 minutes at 2.4 gpm (9.1 L/min) With a Velocity of 167 ft/min (50.9 m/min)

After the initial period at high flow, the erosion rate once again dropped rapidly as surface protection developed until at 60 minutes into the test. The erosion rate was once again below the 5 g/min level (Figure 20). At the 60 minute point in the test there were no plus number 4 size particles collected (Figure 23). Once again the coarse particles were able to adjust to the flow and were effectively protecting the slope.

In another test, the overland flow component was increased to establish the upper resistance of the SRG1 material, (Figure 24). The flow rate was increased to 6.0 gpm (22.7 L/min) with a corresponding velocity increase. The increased severity of the overland flow portion of the event produced a rapid removal of material, creating two deep rill through the full panel height, which included 18 percent plus number 4 size particles collected in from Panel 1 (Figure 25).

Panel 3 of SRG1 was selected for additional testing above the 2.4 gpm overland flow rate. The flow rate with precipitation was increased to 6.0 gpm. The rate of erosion increased 10 fold as the flow rate increased from 5.0 to 6.0 gpm (Figure 26).

The removal of the armoring that had been formed during the prior testing began when the flow reached 6.0 gpm. As can be seen on Figure 27, the surface protection was being destroyed. Slope surface particles as large as 0.75 inches were being transported. In fact a straight channel had been cut in the SRG1, though the channel had not cut through to the Mirafi 6000 material.

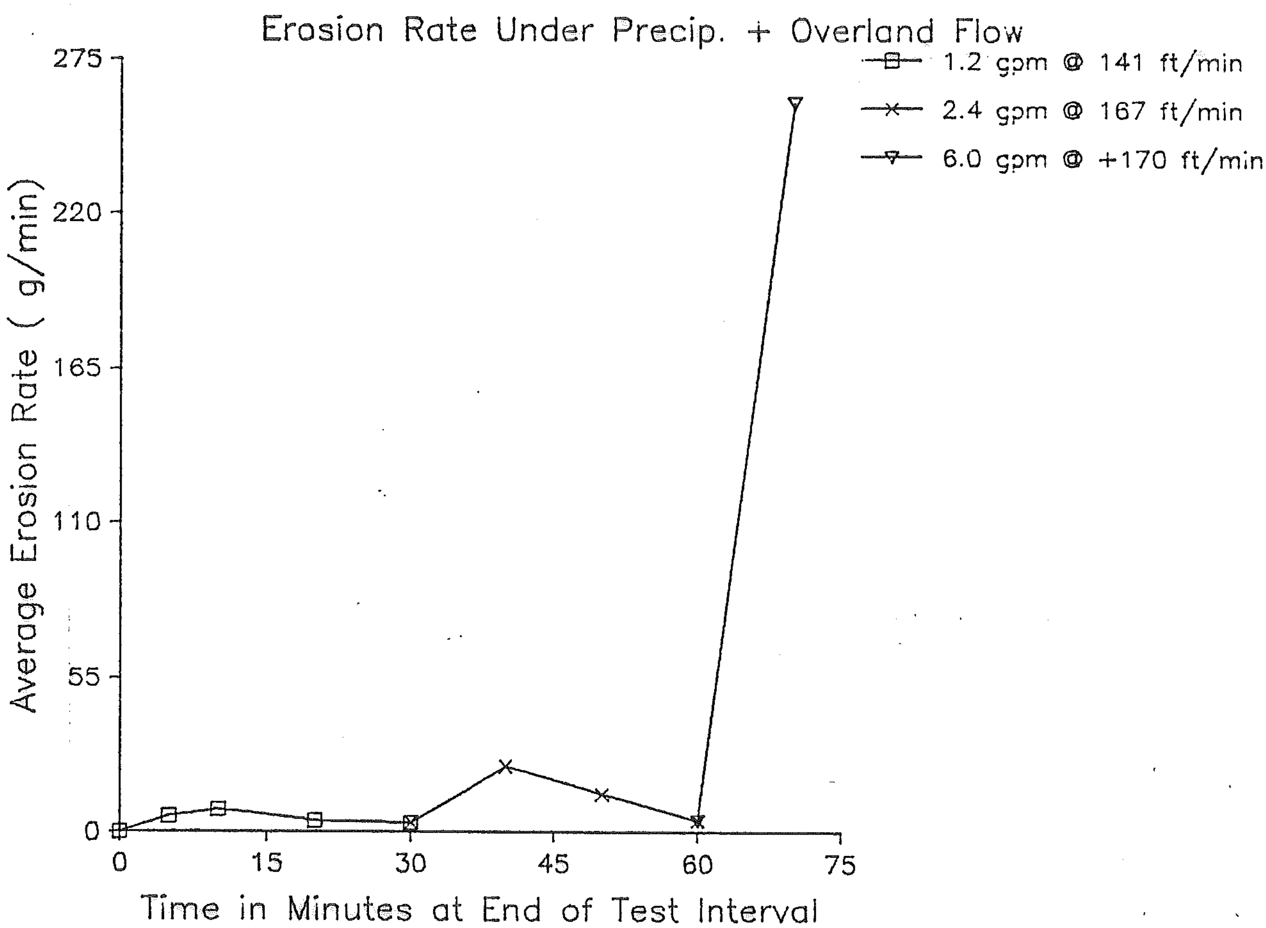

Figure 23. SRG1 Erosion Vs. Time With Flow Quantity and Velocity Varying

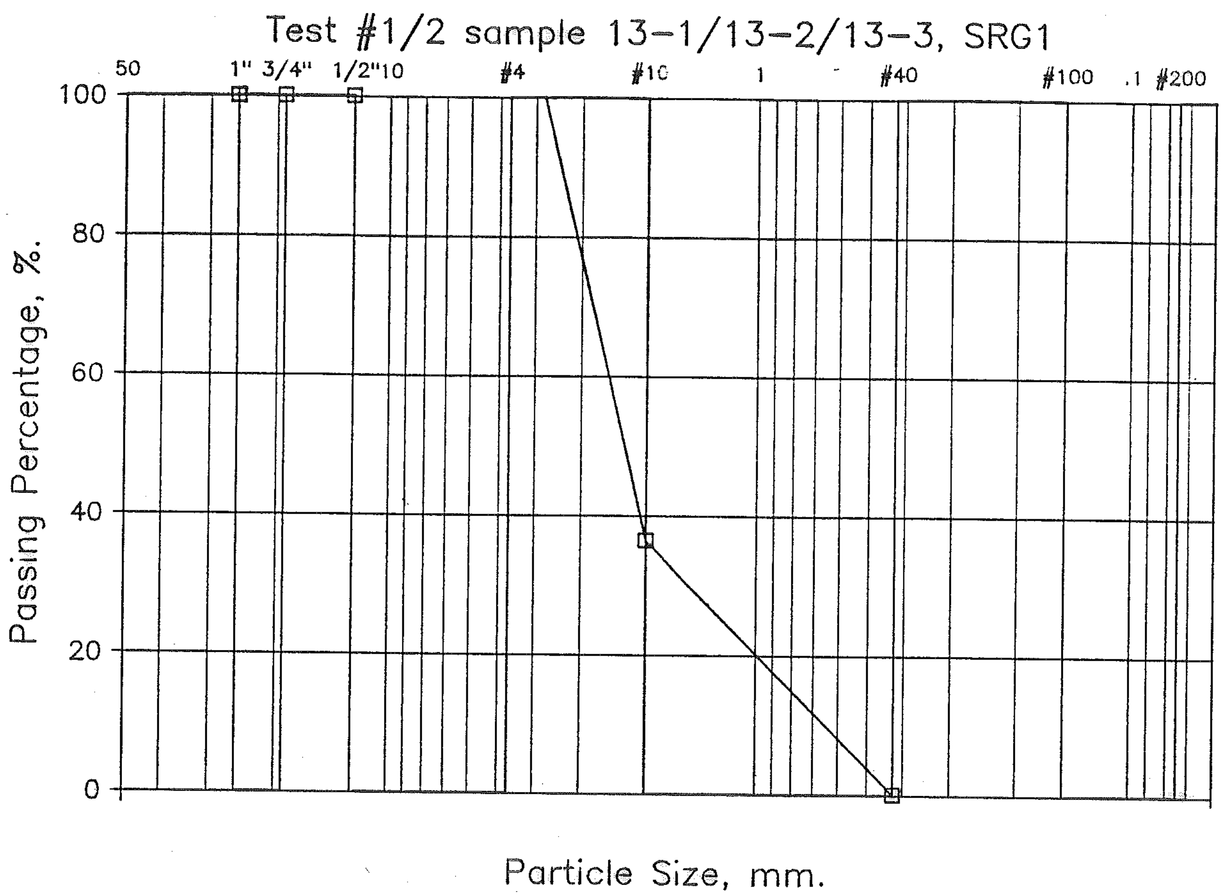

Figure 24. SRG1 Grain Size Analysis, 30 Minutes at 2.4 gpm (9.1 L/min) With a Velocity of 167 ft/min (50.9 m/min)

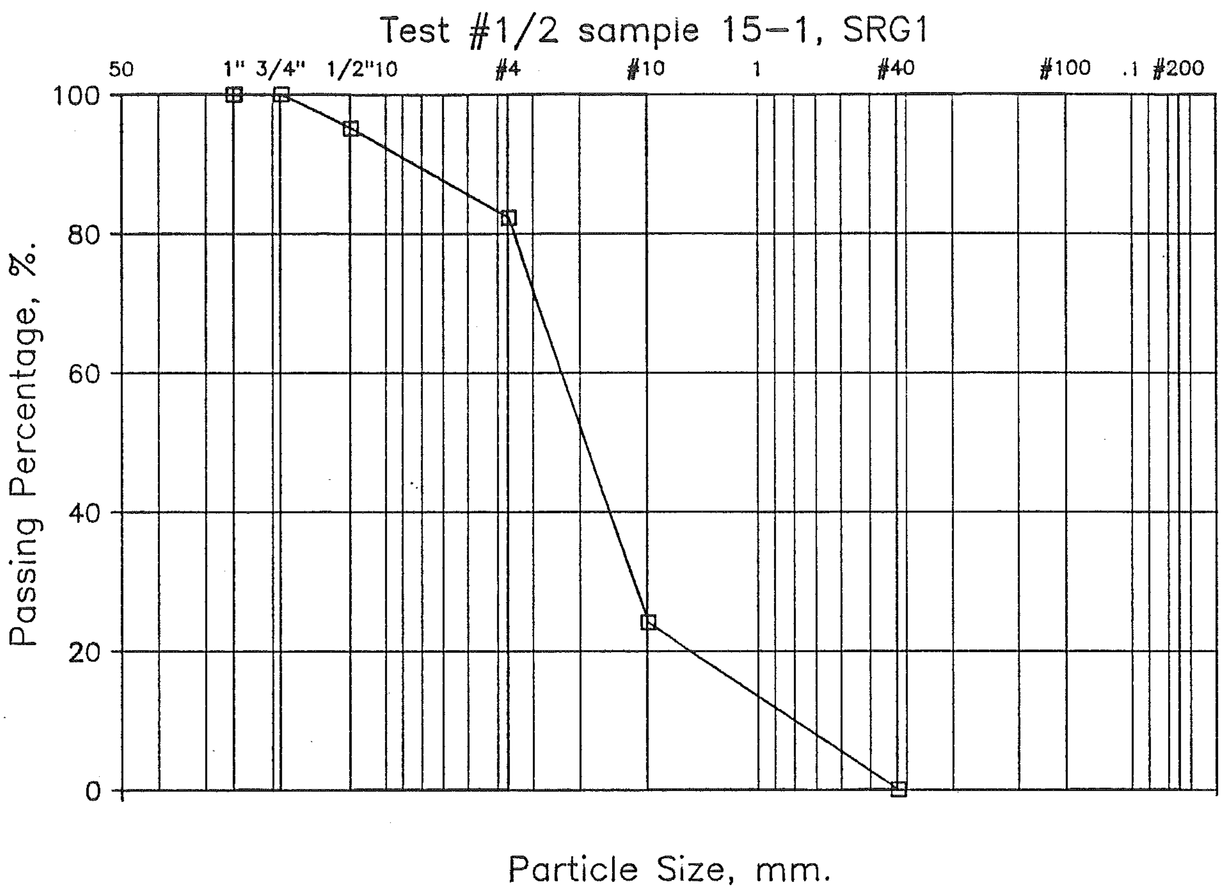

Figure 25. SRG1 Grain Size Analysis, 10 minutes at 6.0 gpm (22.7 L/min) With a Velocity of + 170 ft/min (+51.8 m/min)

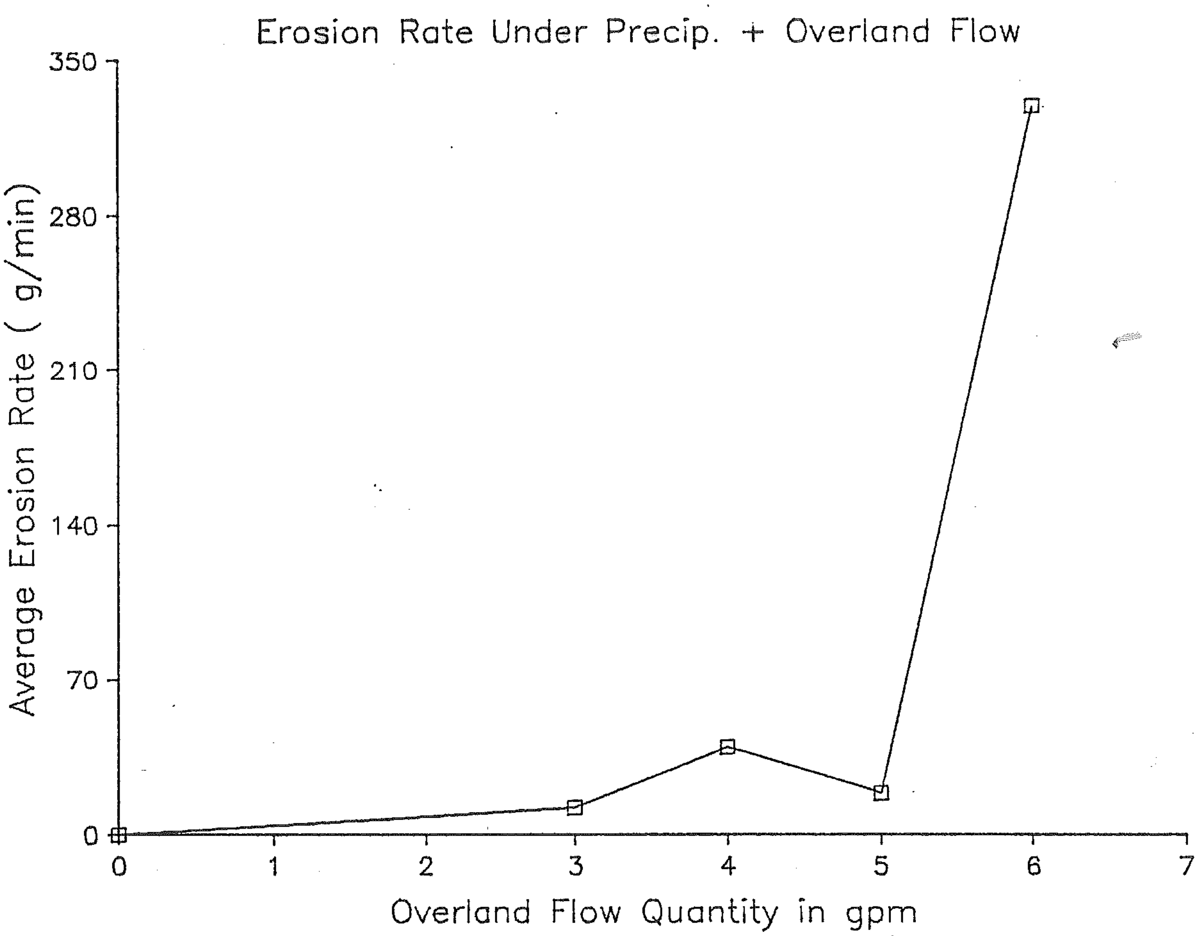

Figure 26. SRG1 Erosion Vs. Overland Flow Quantity,
2:1 Slope With a Flow Velocity of +170 ft/min (+51.8 m/min)

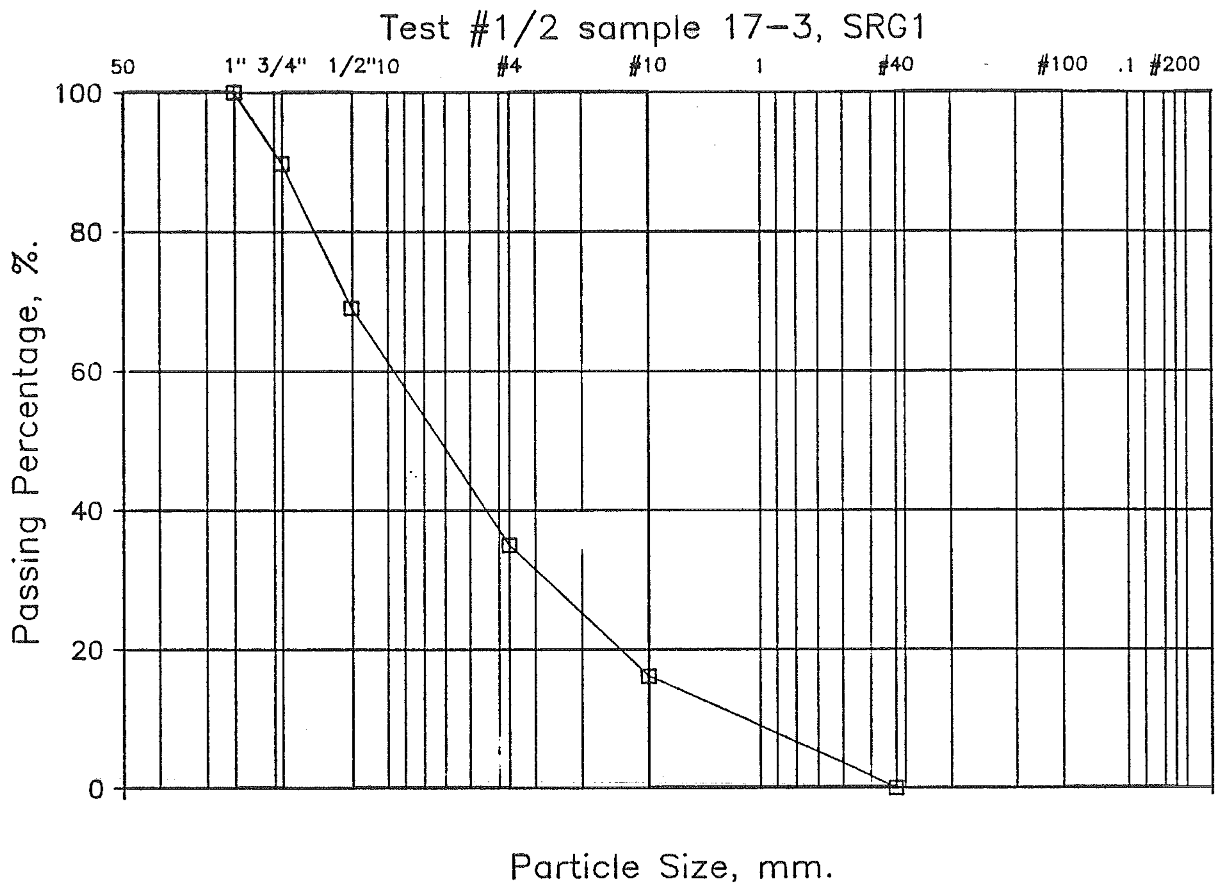

Figure 27. SRG1 Grain Size Analysis, Panel 1, 10 Minutes of Combined Flow at 6.0 gpm (22.7 L/min)

To depict the relationship between erosion rate and overland flow velocity when a 2:1 slope of SRG1 material is stressed by precipitation and overland flow, Figure 28 was prepared. When the flow rate is 1.2 gpm and the velocity is less than 141 ft/min the slope of SRG1 material will armor itself. As can be seen in Figure 28, the erodibility of the SRG1 material was not increasing even when the erosion stress was increasing due to the development of a resistive surface.

All of the data examined so far has indicated that when a soil with the properties of SRG1 is subjected to precipitation and overland flow erosion stresses the soil has a tendency to protect itself. If the material can resist the flow, surface armor will develop. Relationships depicted on Figures 15 and 20 show clearly that with time the rate of erosion will decrease. If the slope is not disturbed then surface protection is available to resist erosion during subsequent flows. Should the surface protection that has developed be damaged then the rate of erosion would increase with the next flow until the armor could be reformed.

Data on Figures 15 and 20 also show that with successively higher flow events the rate of erosion first increases and then rapidly decreases as a more efficient form of surface protection is formed. However, at some point the erosion stresses will become large enough to transport the largest soil particles. When this severe erosion environment is brought to bear on the slope, the slope will fail.

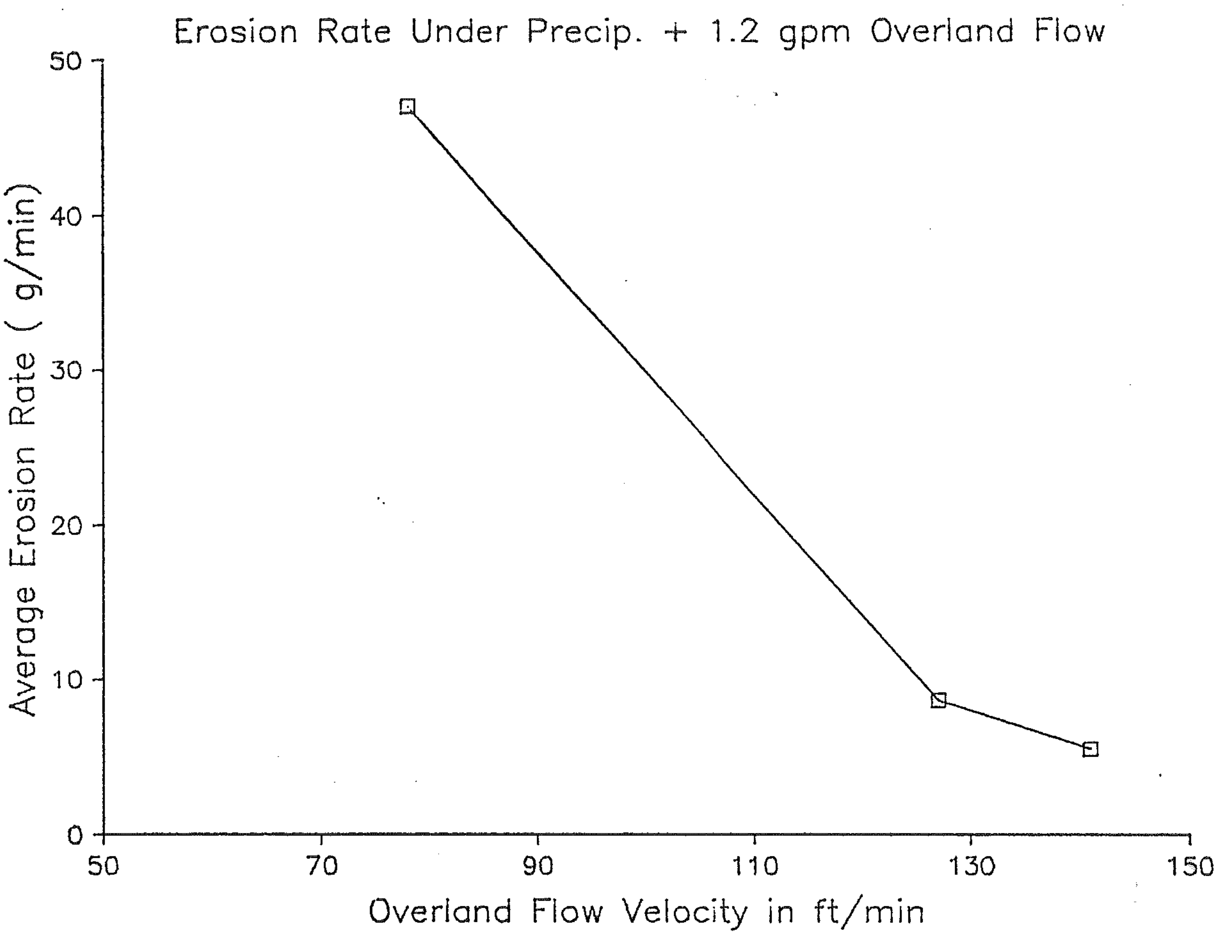

Figure 28. SRG1 Erosion Rate Vs. Overland Flow Velocity, 2:1 Slope and 1.2 gpm (4.5 L/min)

Another test was performed using the SRG1 material. This test examined the resistance to erosion at high overland flow rates while the slope was kept at 2:1. The overland flow was increased to 8.0 gpm (30.3 L/min) which resulted in panel failure for two of the panels, (Figure 29). This data and the data from the first series of SRG1 tests show similar behavior. The precise flow at which the slope fails appears to lie between 6.0 and 8.0 gpm flow rates. The differences between panels is sufficient to produce this range in maximum erosion stress resistance. It is adequate to know the conditions at which stress will have a high probability of producing an erosion channel when SRG1 material is placed on a 2:1 slope. These conditions are met when the precipitation and overland flows are combined and the overland flow component is greater than 4.0 gpm.

An example of the variability to be found on "identical" panel surfaces is depicted on Figure 30. The results of panel 3 present proof that for an advantageous arrangement of surface particles even SRG1 material is resistant to combined flows with an overland component of 8.0 gpm. It should be noted that considerable movement and surface erosion occurred prior to the development of this rather stable surface. The sample at the end of the 8.0 gpm 10 minute event contained no particles larger than the number 4 size. This indicates that the preceding flow events were responsible for the slope resistance (Figure 31).

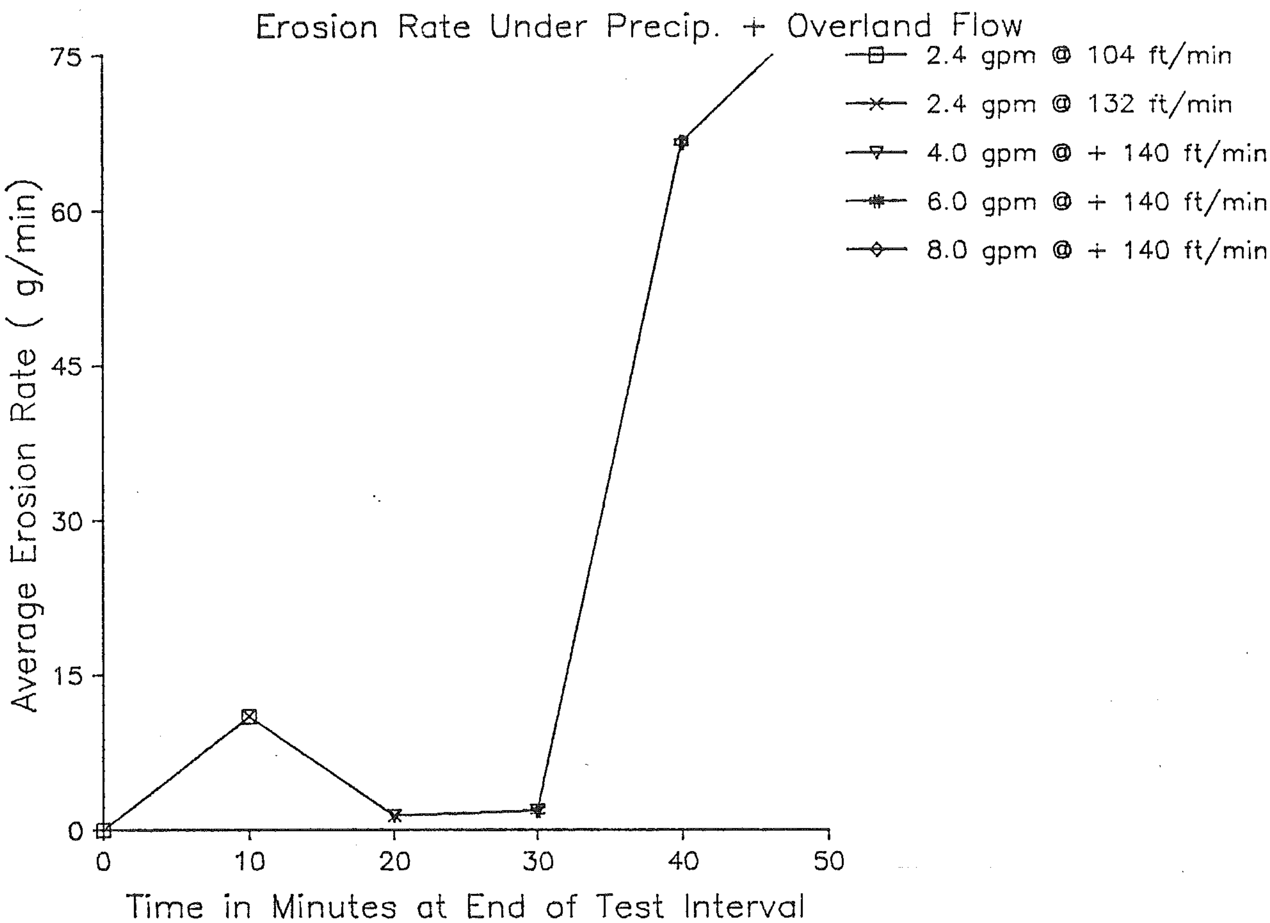

Figure 29. SRG1 Test 2, Erosion Rate Vs. Time, 2:1 Slope and Varying Overland Flow Conditions

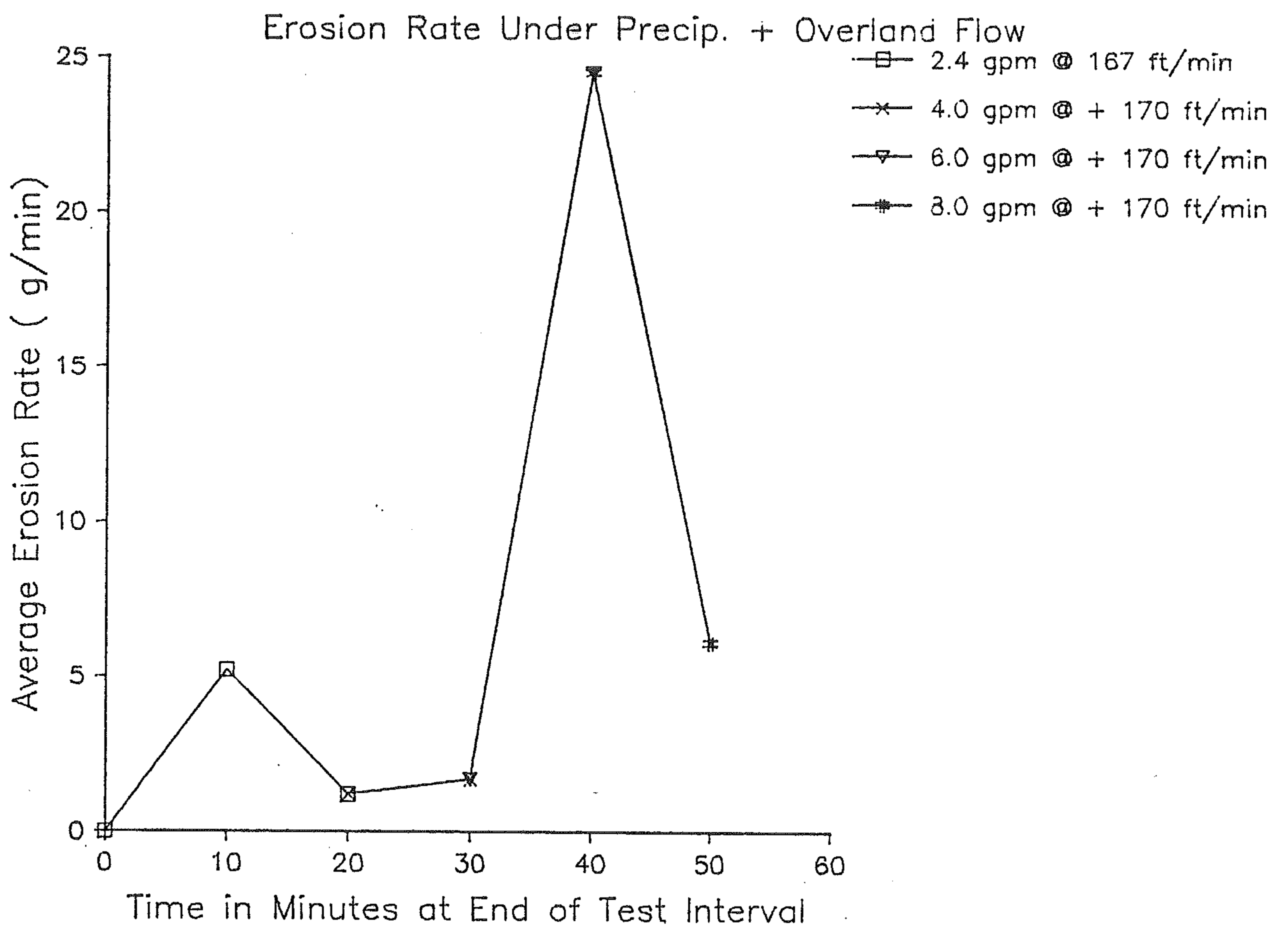

Figure 30. SRG1 Test 2, Panel 3, Erosion Rate Vs. Time, 2:1 Slope

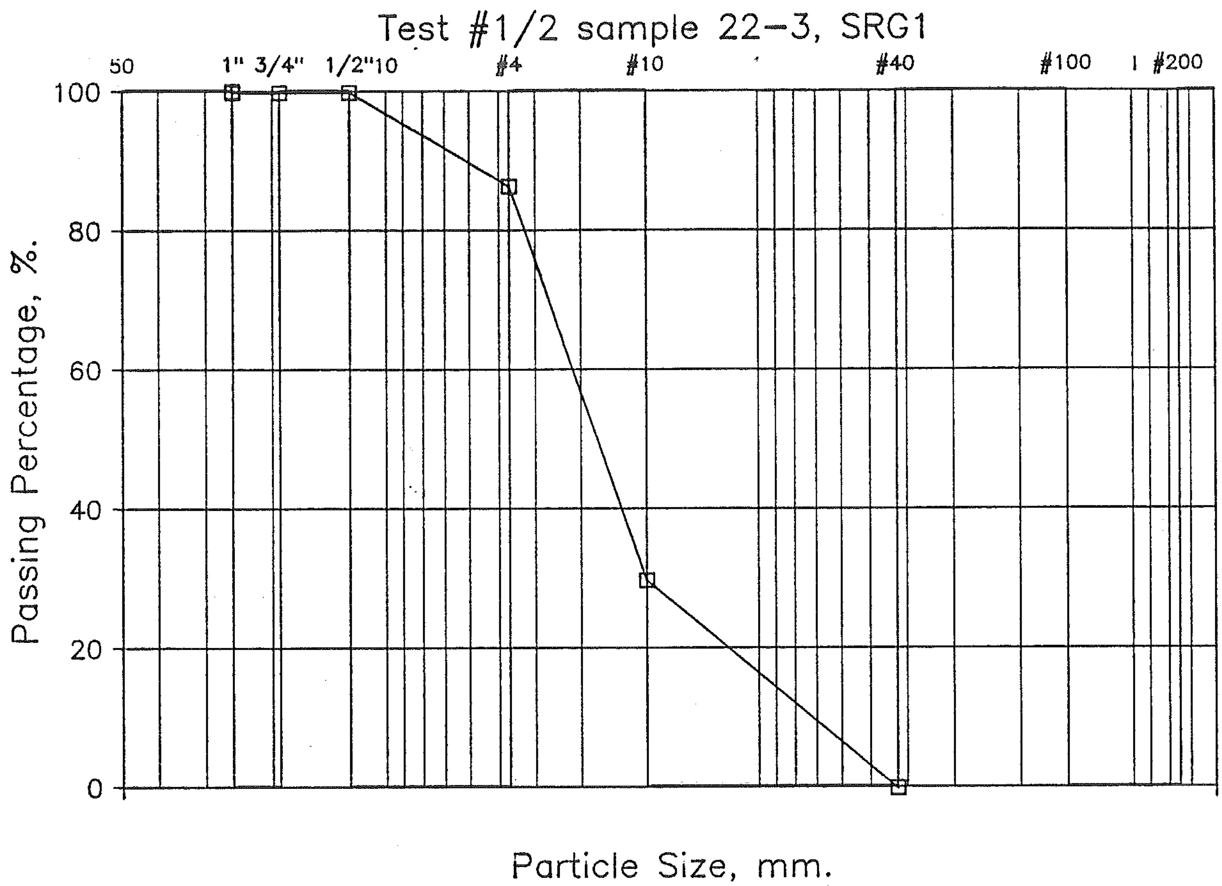

Figure 31. SRG1 Grain Size Analysis, Panel 3, Collected after 10 Minutes of Combined Flow With 8.0 gpm (30.3 L/min)

A sample of the granite surface protection that was placed west of Gilbert Rd. on SR 360, was also tested at 2:1 slopes (SRG8). Panel 1 of SRG8 was very resistant to the combined erosion flow testing until 8.0 gpm was applied (Figure 32). In fact until the failure occurred there was no material removed from the slope. Panels 2 and 3 failed at a combined flow with the overland component at 6.0 gpm although the failure showed more sluffing than the previous channel forming failures (Figure 33). As with panel 1 no material was transported until the failure erosion stresses were applied.

The SRG8 material has a very high permeability. The permeable nature of this material prevented the precipitation and overland flow from causing failure with an overland component up to 6.0 gpm when the slope was at 80 percent of the 2:1 slope (Figure 34). All three panels were able to resist eroding to failure. When the slope was increased to 2:1, one panel was able to resist the 6.0 gpm condition though the other two panels did not exhibit formation of channels. The material was so permeable that no surface flow could be sustained below 6.0 gpm. Without surface flow erosion would not occur under test conditions.

To assess the effect of dust and maintenance activities in adding material that would eventually reduce the permeability on slopes, the test was modified. The SRG8 was placed as for the first two test series then 1300 g of minus number 40 soil derived from SRP5 and IP9 was sprinkled on each test panel. Each panel was wetted from the spray heads alone until the soil

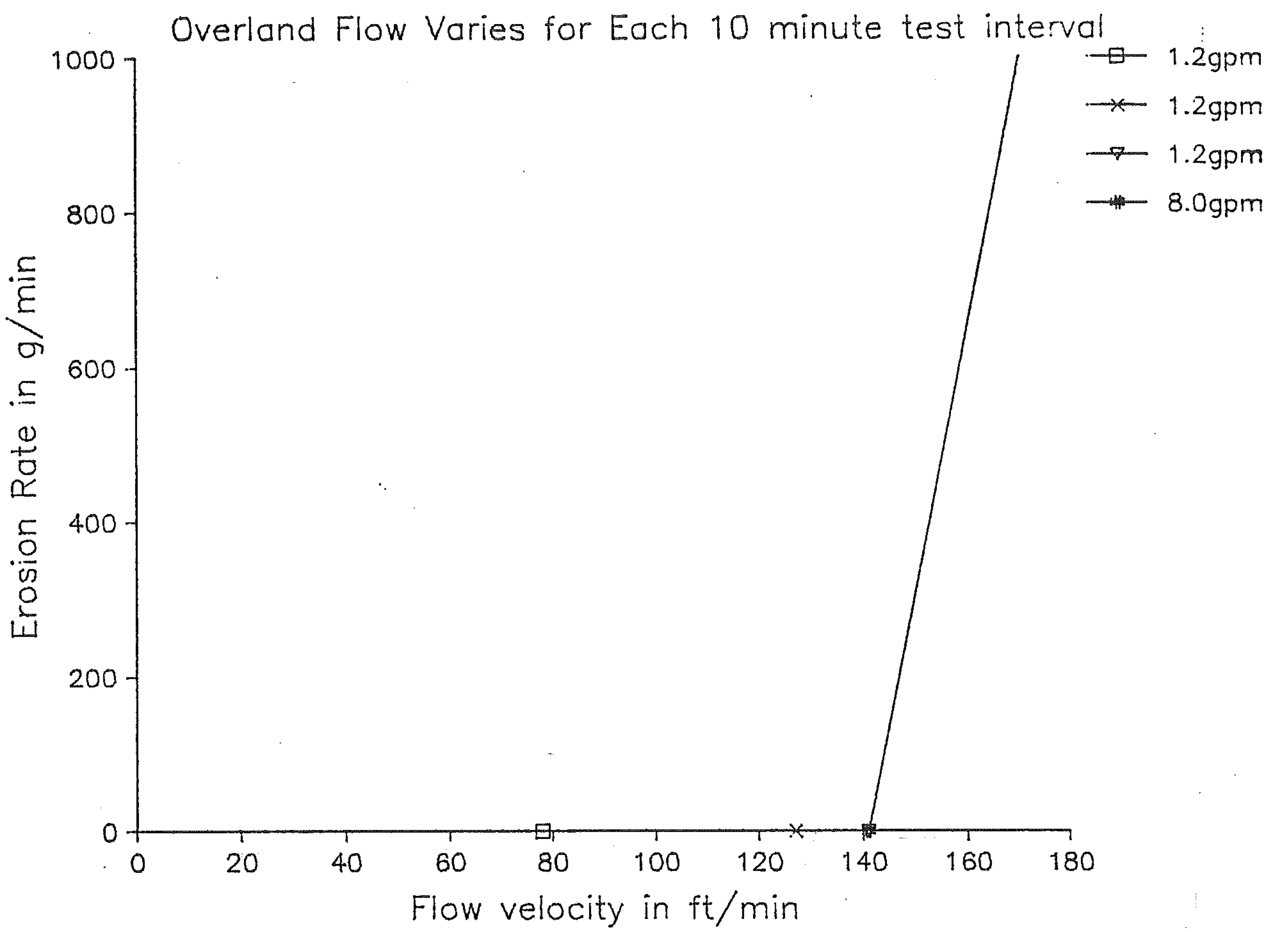

Figure 32. SRG8 Panel 1, Erosion Rate Vs. Flow Velocity, 2:1 Slope

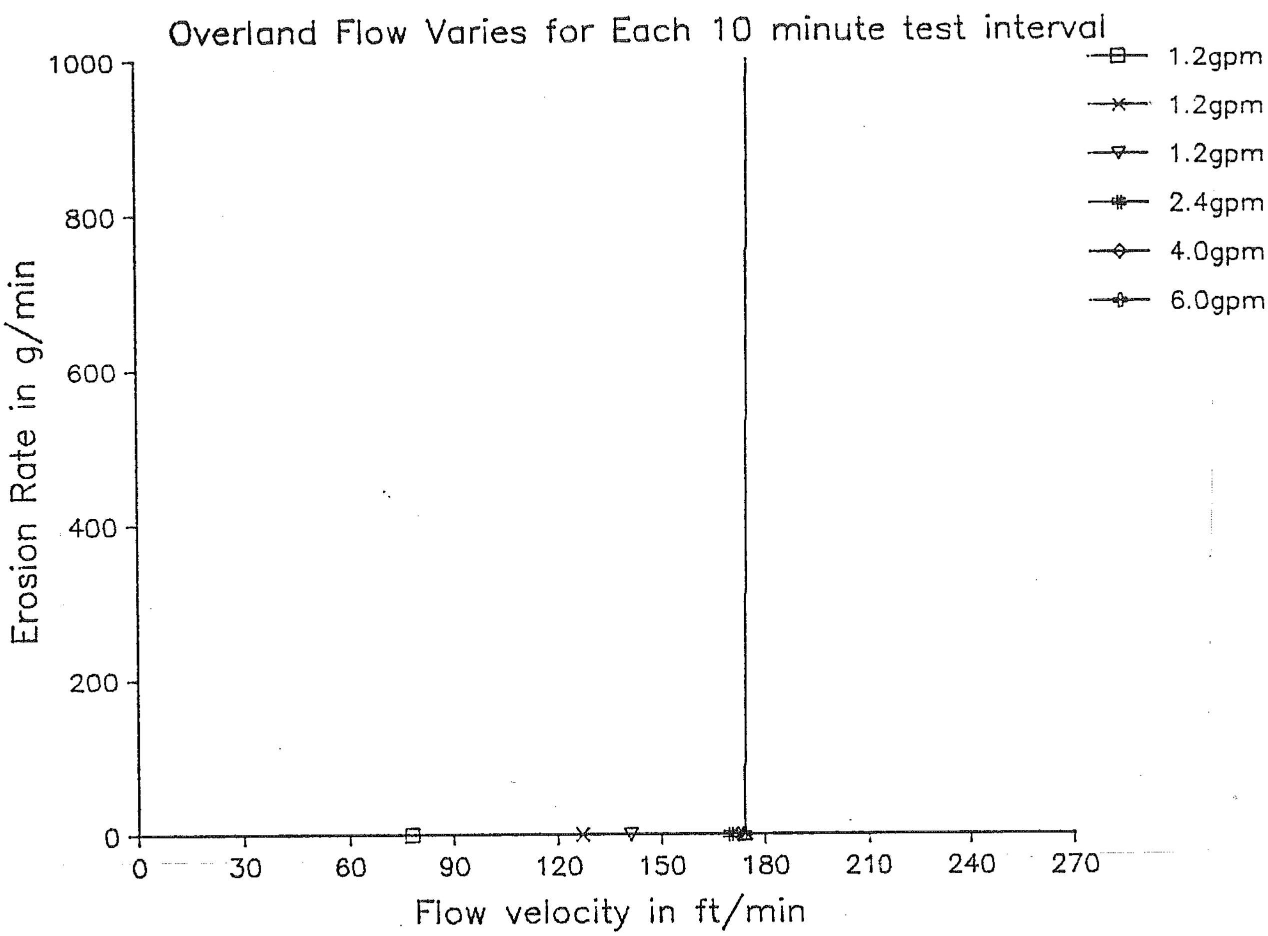

Figure 33. SRG8 Panels 2 & 3, Erosion Rate Vs. Flow Velocity, 2:1 Slope

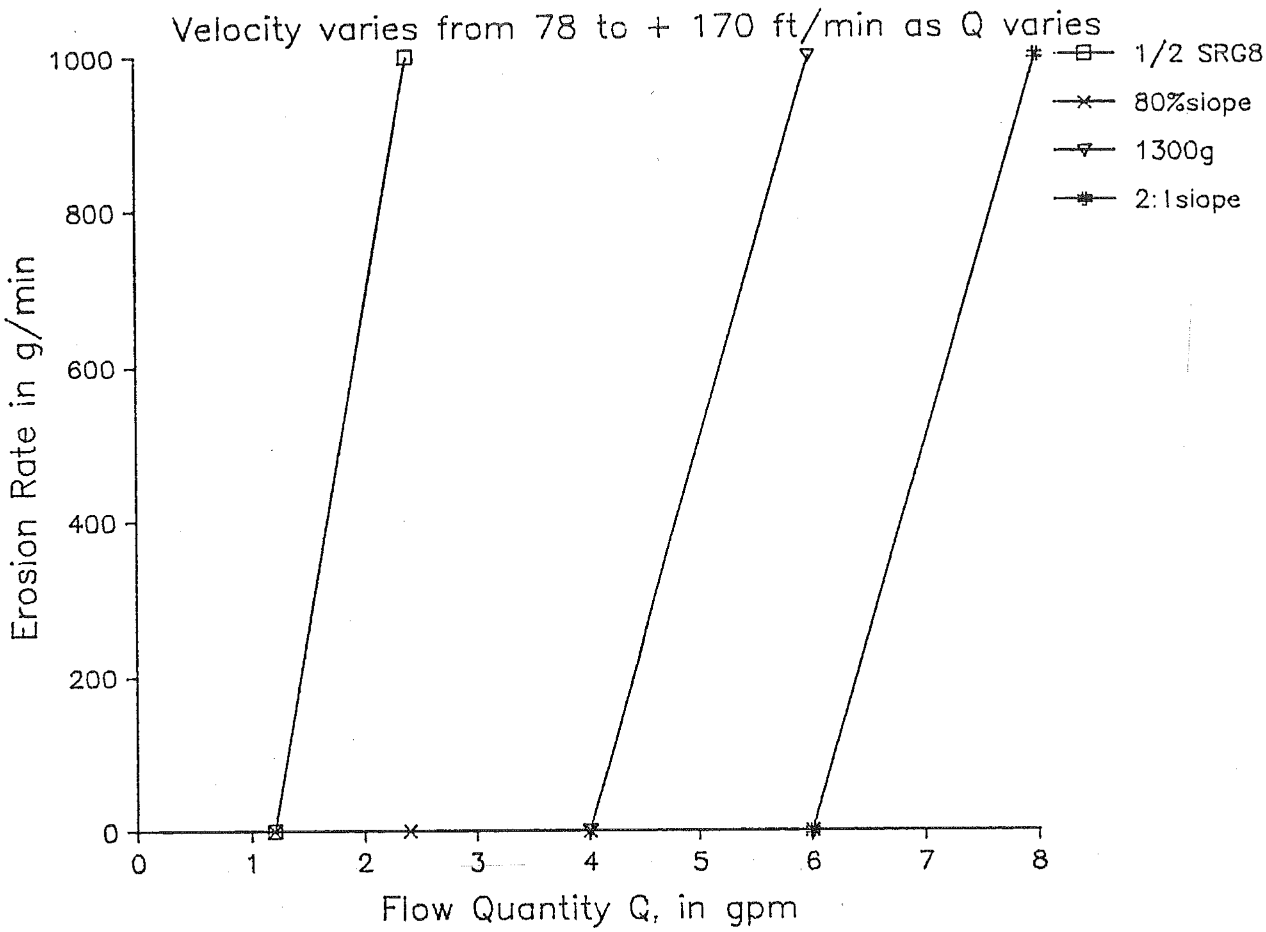

Figure 34. SRG8 Erosion Rate Vs. Flow Quantity
for 26.6 and 21 Degree Slopes

had been transported into the pore spaces of the SRG8. The erosion testing then proceeded with the combined effects of precipitation and overland flow. With the 2:1 slope all panels failed within seconds of applying the combined flow with an overland component of 6.0 gpm (Figure 34). The failure was rapid and took the form of a clear channel until the 6000 material was exposed. There was no question that an erosion failure had occurred (Figure 34).

One additional test series was performed using the SRG8 material. That test modeled the field condition in which a thin 0.5 inch thick layer of SRG8 was placed over a thick layer of low permeable soil. SRP5 was used for the underlaying material and 0.5 inches of SRG8 were placed over it. This test condition examined the erosion resistance when the permeability remained high but due to the thin section water would be forced to move across the surface. When tested under the combined flow conditions with an overland component of 2.4 gpm failure occurred for all panels (Figure 34).

It is of interest to note that the rills produced in the test panels under the last two series of tests looked remarkably similar to the rills observed west of Gilbert Rd. following the referenced storms. Shape and dimensions of both field and laboratory channels were approximately the same.

This series of tests using the SRG8 material was enlightening because it demonstrates the complexity of the slope erosion environment both as placed and as it may potentially change with time. It is not enough to perform a slope erosion test and then proclaim the success when little or no erosion occurs. Instead, the slope designer must understand why the erosion resistance is high and thus why the test is successful. If the results are due to high permeability then the role of thickness and long term permeability in future erosion resistance must be developed. Insufficient knowledge now exists to enable the time plugging relationship to exist for any slope protecting material. However, the designer does not need that specific information, it is sufficient to recognize that time effects will reduce the protection. When that knowledge exists, the designer can at least build redundancy into the protection system or avoid using the materials unstable with time.

The interest in the role of thickness led to another series of tests using material that came from Dysart Rd. and I-10 and designated as IG1. The IG1 material was also used for slope protection on the overpass at Dysart Rd. It possessed a high surface permeability similar to the SRG8 samples. A series of tests terminating with a combined flow environment containing an overland component of 2.4 gpm with a velocity of 167 ft/min produced neither sediment nor failure (Figure 35).

The IG1 material prevented surface flow from developing and thus resisted erosion. A new series of panels were prepared with a 0.5 inch thick layer of IG1 over SRP5 material. The testing was repeated but this time the panels failed when the minimum combined flow with an overland component of 1.2 gpm was applied, Figure 35. The reduced thickness could not support the flow within the section. As soon as flow occurred on the sur-

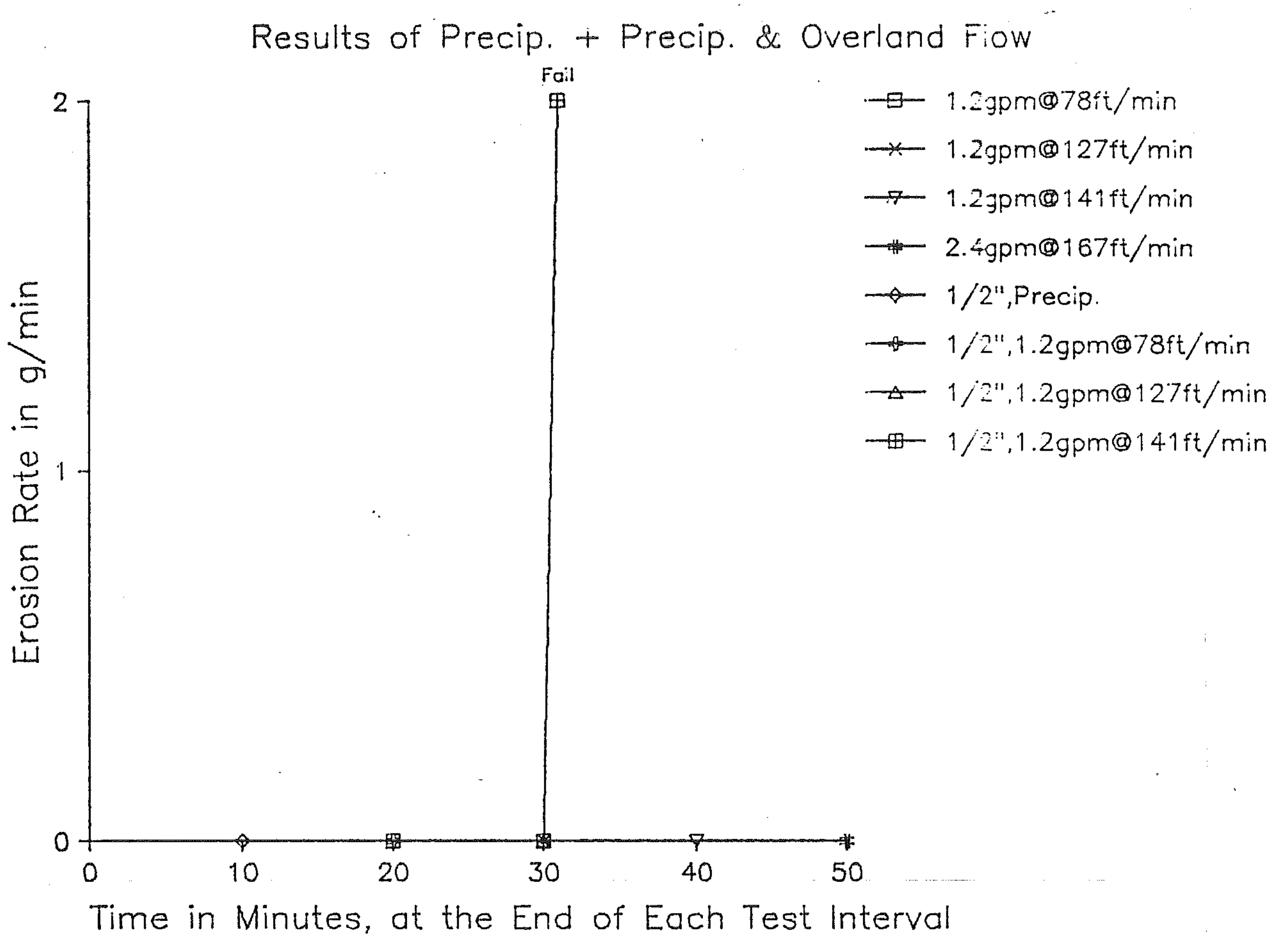

Figure 35. IG1 & 1/2 " IG1, Erosion Rate Vs. Time, 2:1 Slope

face the rather small particles could not resist transport. Because the particles were all approximately the same size no larger particles were available to protect the smaller ones. Therefore when the erosion started it proceeded rapidly to failure. With respect to the speed of failure the development of channels, resembled a piping failure in fine grained soil.

The erosion channels that formed in the laboratory were similar in geometry to those observed at the Dysart Exchange that were produced from the rumble strip discharge over the slopes. Like the SRG8 materials the correlation between field and laboratory for the IG1 panels was remarkably good.

The reported testing to this point has dealt with materials that have been used on the slopes as protection. A soil, IP9, was selected for testing because unlike the IG1, SRG1, and SRG8 materials it had only six percent of particles larger than the number 4 size (Table 14). Unlike the other materials it had failed during precipitation testing while at the 2:1 slope (Figure 36). This soil could not develop an effective armoring system because of the paucity of plus number 4 size particles. Without these particles and with the low permeability that produced efficient runoff, the slopes were doomed to fail. In fact an interesting phenomena is expressed in the data (Figure 36). It should be noted that in all prior tests that produced sediment, the initial increase in rate of erosion was followed by a drastically reduced rate. This was hypothesized as the result of initially unstable coarse particles moving to achieve

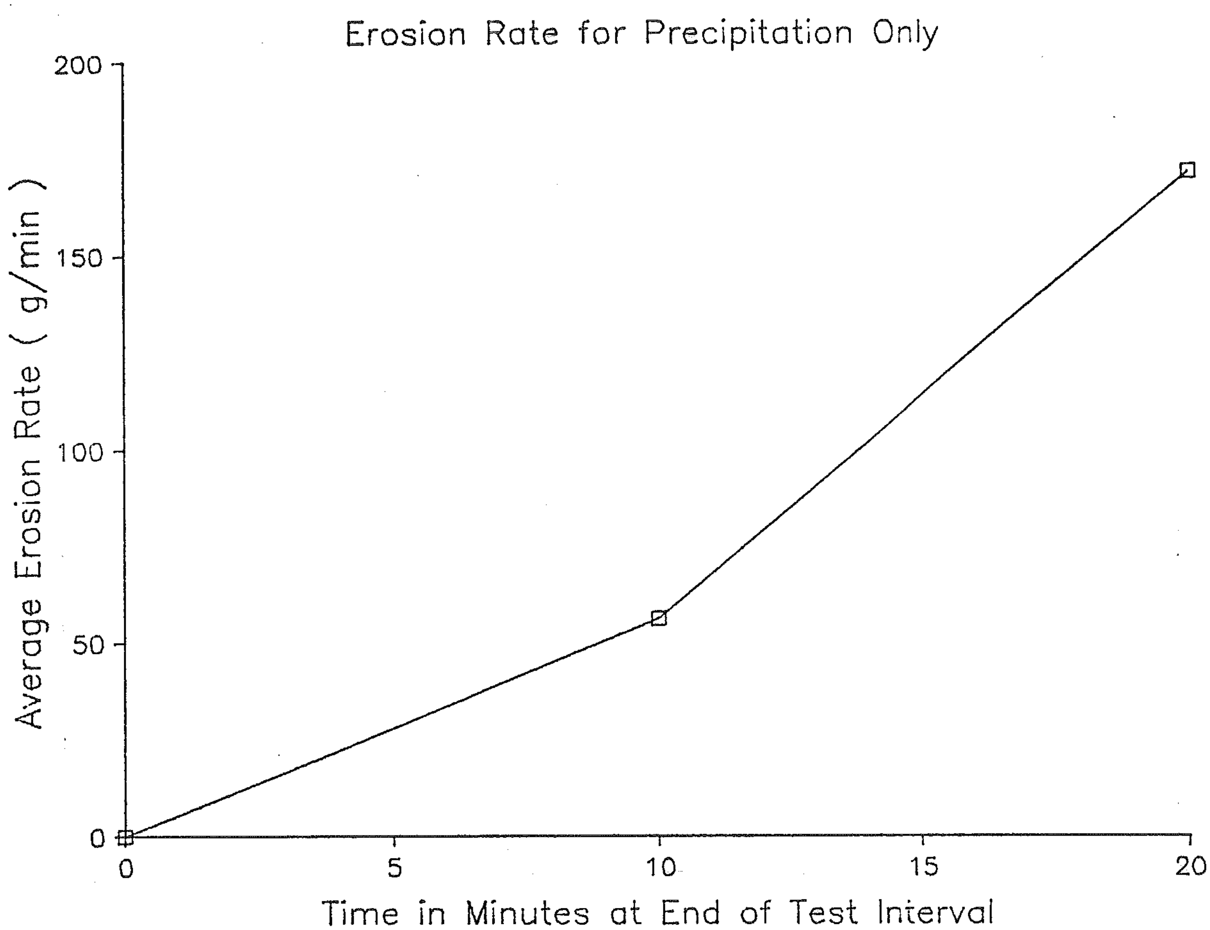

Figure 36. IP9 Erosion Rate Vs. Time, 2:1 Slope

a more stable orientation. For the IP9 soil, there were not enough coarse particles to have any affect.

The IP9 panels appeared to express the development of microchannels on the surfaces. Without the development of incise resisting surface armoring, rills were incised in the surface. As the duration of flow persists these rills drained larger and larger portions of the surface. Each rill was in effect developing an overland flow component that increased minute by minute. The net effect of this increasing flow is the acceleration of the erosion rate to failure. The test results from IP9 are graphic indicators of erosion when the development of armoring is lacking.

One final observation on the IP9 test results also deals with the small amount of coarse particles in the soil. During the initial three minutes of the test a marked change in the appearance of the panel surfaces. occurred. Each panel's color lightened as the lighter colored larger soil particles were exposed. The finer particles were washed away leaving the sand and what few gravel particles behind. In effect, armoring was occurring, however, there was an insufficient amount of these particles left behind to link together. Without the linking or buttressing of each other these particles could not prevent the incisement of small channels. Once the incisement process started, the flow regime was able to transport larger and larger particles from the surface. The analogy of a piping failure is applicable since with piping each particle removed increases the gradient; thus the rate of removal increases.